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OFFSHORE OIL AND GAS PRODUCTION WASTE CHARACTERISTICS, TREATMENT METHODS, BIOLOGICAL EFFECTS AND THEIR APPLICATIONS TO CANADIAN REGIONS

Final Report

By

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OFFSHORE OIL AND GAS PRODUCTION WASTE CHARACTERISTICS, TREATMENT METHODS, BIOLOGICAL EFFECTS AND THEIR APPLICATIONS TO CANADIAN REGIONS

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RESUME

Le présent rapport évalue les déchets rejetés de certaines plates-formes de production de pétrole et de gaz situées en mer. Il examine également des pratiques actuelles pouvant être utilisées dans les régions marines canadiennes où l'on prévoit installer des plates-formes de production. Les objectifs précis de ce rapport sont:

(1) de résumer les charactéristiques des déchets de production provenant des champs pétrolifères et gazifères actuellement exploités en mer, les quantités rejetées et les pratiques d'élimination employées;

(2) de comparer les techniques et les pratiques de pointe avec celles actuellement utilisées pour le traitement et l'élimination des déchets provenant de la production de pétrole et de gaz en mer, entre autres du point de vue coût et efficacité;

(3) d'examiner les effets néfastes connus et potentiels que peuvent avoir, sur l'environnement marin, les déchets provenant de la production en mer de pétrole et de gaz;

(4) d'évaluer l'importance relative des rejets futurs de déchets provenant de la production de pétrole et de gaz dans les eaux marines canadiennes;

(5) d'évaluer les lacunes dans les données disponibles qui limitent leur utilisation au Canada, et de présenter des recommandations concernant les priorités futures en matière de recherche.

Le rapport examine les déchets produits aux plates-formes de production de pétrole et de gaz situées en mer et qui sont rejetés sur place ou transportés sur terre afin d'y être traités et éliminés.

L'examen des documents et l'étude des pratiques en vigueur dans l'industrie ont porté sur trois régions marines productrices des États-Unis: le golfe du Mexique, la côte californienne et l'anse Cook, en Alaska, ainsi que sur les champs producteurs de la mer du Nord situés près du Royaume-Uni et de la Norvège. Les résultats de cette étude ont été appliqués à trois régions marines du Canada ayant un potentiel de production de pétrole et de gaz, c'est-à-dire la plate-forme Scotian, les Grands Bancs de Terre-Neuve et la mer de Beaufort.

Les principaux rejets étudiés dans ce rapport sont:

- les eaux gisement
- les fluides et les déblais de forage
- les eaux de ballast
- les eaux de stockage

Cette évaluation est basée sur les quantités de déchets rejetés dans l'océan et sur les quantités de contaminants (hydrocarbures, métaux lourds et additifs) provenant de ces déchets, ainsi que sur l'importance accordée à ceux-ci par les organismes de réglementation gouvernementaux, l'industrie, les spécialistes du domaine environnemental et les chercheurs en général.

Les rejets secondaires examinés dans ce rapport sont:

- le sable produit
- les écoulements de pont
- les fluides provenant de l'achèvement et du reconditionnement des puits
- les divers fluides des puits (ciment, obturateur anti-éruption)
- déchets sanitaires et domestiques
- déchets provenant du traitement du gaz et du pétrole
- rejets divers
  - rejets de fabrication
  - eaux de refroidissement
  - saumure de dessalement
  - eaux de vérification du système d'extinction

Les quantités de déchets et de contaminants provenant de ces rejets secondaires sont faibles comparativement à celles provenant des rejets principaux.

Le rapport décrit les moyens actuellement utilisés dans chaque région pour le rejet et l'élimination de tous les déchets. Il présente également une évaluation, sur les plans technique et financier, d'autres méthodes permettant d'éliminer l'eau produite et les fluides et déblais de forage.

On y passe en revue la nature et le rendement des pratiques actuelles de traitement des déchets. Cela comprend une comparaison des installations de traitement situées sur terre et en mer. Les plus récentes techniques de traitement des eaux contaminées par le pétrole, des déblais de forage et des eaux d'égout y sont également décrites. On évalue l'applicabilité des méthodes de traitement et d'élimination habituelles aux régions marines du Canada. Les effets aigus et sublétaux des déchets entiers et de leurs éléments toxiques, y compris les produits chimiques industriels, sont évalués à partir de cas particuliers et d'études en laboratoire; on insiste surtout sur les indications de bioaccumulation de métaux lourds et d'eléments organiques dans le biote marin.

Le rapport décrit les règlements concernant les rejets de déchets en mer dans les zones de production d'hydrocarbures de la Norvège, du Royaume-Uni et des États-Unis. Il donne également une comparaison des conventions et des lois internationales qui régissent les divers déchets provenant de la production pétrolière et gazière.

Il donne des scénarios de production et évalue les caractéristiques et les quantités de déchets pour les installations marines futures, de la plate-forme Scotian, des Grands Bancs de Terre-Neuve et de la mer de Beaufort. Les scénarios décrits ont été élaborés en prenant pour modèle des grands champs producteurs, mais ne sont pas particuliers à un emplacement précis. On y donne les concentrations de fond des hydrocarbures et des métaux lourds présents dans les sédiments et dans l'eau de mer pour chacune des trois régions marines canadiennes. Les zones d'influence sont estimées à l'aide d'un modèle tridimensionnel de dispersion appliqué à une grandeur scalaire passive; le modèle étudie également les effets de l'advection et de la flottabilité. On trouve aussi des données océanographiques particulières à chaque région.

Les risques biologiques associés aux déchets de production sont partagés en deux catégories pour chacune des trois régions marines: ceux qui sont considérés importants et ceux qui ne posent pas de problèmes.

Les conclusions et les recommandations ont été formulées conjointement par les principaux auteurs du rapport et constituent un résumé des divers examens effectués dans le document; elles sont présentées sous cinq rubriques:

(1) importance relative des déchets provenant de la production en mer;

(2) conclusions concernant les règlements sur les rejets;

(3) lacunes qui, sur le plan des données, limitent les possibilités d'un développement marin non préjudiciable à l'environnement et l'adoption de règlements judicieux au Canada;

(4) recommandations concernant les recherches futures au Canada; et

(5) suggestions de moyens de surveillance du développement marin au Canada.

SUMMARY

This report contains an evaluation of wastes discharged from existing oil and gas production platforms in selected offshore producing regions. It also includes an assessment of existing practices as they affect Canadian offshore regions where future production is anticipated. The specific objectives of the report are to provide:

(1) A summary of production waste characteristics, volumes and disposal practices for existing offshore oil and gas production fields;

(2) A comparison of existing and state-of-the-art treatment technologies and disposal practices used for offshore oil and gas production wastes, including their cost and effectiveness;

(3) A review of known and potential adverse effects of wastes discharged from offshore oil and gas production platforms on the marine environment;

(4) An assessment of the relative importance and significance of future oil and gas production waste discharges in Canadian offshore waters;

(5) An assessment of deficiencies in existing data which limit their application to the Canadian situation, and recommendations for future research priorities.

The report examines wastes which are generated at offshore oil and gas production platforms and discharged on-site or transported to shore for treatment and disposal.

The review of literature and industry practice deals with three U.S. offshore producing regions: Gulf of Mexico, California coast and Cook Inlet, Alaska; and, the U.K. and Norwegian sectors of the North Sea producing fields. The results of this review and evaluation have been applied to three Canadian offshore regions with potential for production of oil and gas; namely, the Scotian Shelf, Grand Banks and Beaufort Sea.

The major discharges from offshore oil and gas production activities discussed in this report are:

- produced water
- drilling fluids and cuttings

- ballast water
- storage displacement water

These have been assessed as major wastes based on the volumes of waste discharged to the ocean and the amount of contaminants (hydrocarbons, heavy metals and exotic additives) associated with these discharges, and the importance which has been placed on these waste discharges by government regulatory agencies, industry, environmental scientists and researchers in general.

Minor discharges from offshore production discussed in the report are:

- produced sand
- deck drainage
- well completion and workover fluids
- miscellaneous well fluids (cement, BOP fluid)
- sanitary and domestic wastes
- gas and oil processing wastes
- miscellaneous discharges
  - slop oil
  - cooling water
  - desalination brine
  - fire control system test water

Waste volumes and inputs of contaminants from these minor wastes are small compared with those for the major wastes.

Current discharge and disposal practices for all wastes are described for each region. Technical and cost evaluations of alternative methods for disposal of produced water and drilling fluids and cuttings are presented.

A review of existing waste treatment practices and performance is presented. This includes a comparison of onshore and offshore treatment facilities. State-of-the-art treatment technologies for oily water, oil-wet drilling cuttings, and sewage are also given. The applicability of typical treatment and disposal practices to Canadian offshore areas is also evaluated. Acute and sub-lethal effects of whole

wastes and their toxic constituents, including process chemicals, are evaluated from case histories and laboratory studies; emphasis is placed on reviewing the evidence for bioaccumulation of heavy metals and organic compounds in marine biota.

Marine discharge regulations used in the offshore hydrocarbon production areas of Norway, the United Kingdom and the United States are presented. The report also gives a comparison of international conventions with legislation for oil and gas production, for various wastes.

Production scenarios and estimates of waste discharge characteristics and volumes are given for future offshore production in the Scotian Shelf, Grand Banks and Beaufort Sea. The scenarios used are typical of world-scale offshore production facilities but are not site-specific. Background concentrations of hydrocarbons and heavy metals in sediment and sea water for each of the three Canadian offshore areas are presented. Zones of influence are estimated using a three-dimensional dispersion model for a passive scalar quantity; the model includes the effects of diffusion, advection and buoyancy. Input data include oceanographic data specific to each area.

The biological concerns associated with the production wastes are divided into those judged to be of significance and those which can be considered non-issues for each of the three Canadian offshore regions.

Conclusions and recommendations formulated collectively by the principal authors of the report are presented. They represent a synthesis of the various disciplinary reviews contained within the report and are presented under five topics:

(1) relative importance and significance of offshore production wastes;

(2) conclusions regarding discharge regulations;

(3) information deficiencies limiting environmentally sound offshore development and regulation in Canada;

(4) recommendations for future research in Canada; and

(5) approaches to offshore monitoring in Canada.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations were formulated at a workshop attended by the five principal authors of the report. The experience and disciplines of these authors comprised chemistry, process engineering, waste treatment engineering, marine ecology and chemical oceanography. A structured workshop format known as the Nominal Group Technique (Delbecq et. al. 1975)[1] was used to facilitate the formulation of collective judgements for each of the five topics (sections):

1) relative importance and significance of offshore production wastes;
2) conclusions regarding discharge regulations;
3) information deficiencies limiting environmentally sound offshore development and regulation in Canada;
4) recommendations for future research in Canada;
5) approaches to offshore monitoring in Canada.

This approach was used to allow each conclusion and recommendation to be a synthesis of the various disciplinary reviews contained in Chapters 2 to 8. As a result, the conclusions and recommendations do not coincide with the topic-by-topic formats of Chapters 2 to 8 but rather represent a synthesis of the entire work conducted for this study. The conclusions and recommendations are directed at effective use of the document by environmental managers, research managers, regulatory officials and government and industry decision-makers.

Each conclusion in Section 1. is followed by references to those report sections which provide detailed information and a rationale for the conclusion. These conclusions draw on the experience of operators in current offshore producing regions (Gulf of Mexico, coastal California, Cook Inlet and North Sea) reviewed during the study, and are relevant to future Canadian offshore production. They are organized by waste constituent and source of the waste.

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[1] Delbecq, A.L., A.H. Van de Ven and D.H. Gustafson. 1975. Group techniques for program planning. Scott, Forseman and Company. Glenview, Illinois.

The conclusions in Section 2. are a synthesis of the strengths and weaknesses of the various regulatory systems currently used in offshore producing countries (United States, Norway, United Kingdom) and represent a regulatory framework that the principal authors judge to be sufficient, workable and efficient for environmental control of offshore oil and gas production.

Sections 3., 4. and 5. are recommendations on data deficiencies and future research and monitoring, based on the authors' understanding of work done to date in Canada and other countries, and are directed at future Canadian offshore production.

1.0 Relative Importance and Significance of Offshore Production Wastes

Three groups of chemical compounds that are discharged in various forms from offshore oil and gas production operations are significant in terms of the quantities discharged (loading to the sea); the treatment technology and management (operating) practices employed; and their potential biological effects:

- Hydrocarbons - Refined and Crude Oils, Aromatic Content in Particular
- Persistent Chemicals and Chemicals Which Do Not Occur in Nature
- Metals

1.1 Conclusions: Crude Oil

(a) Residual crude oil constituents in produced water, following treatment by gas flotation and surface or subsea discharge, result in a total oil content of approximately 40 mg/L and an aromatic hydrocarbon content of 5-10 mg/L. While total oil discharges at this level are not known to cause persistent and widespread effects, long-term accumulation of aromatic compounds in the marine environment may occur when many oil fields are in production and are generating large volumes of produced water later in the life of each field. These accumulations occur mostly in local sediments and possibly, to a lesser and unknown degree, in the water column. (Chapter 2, Section 1.4; Chapter 5, Section 1.2.2; Chapter 8, Table 8-15)

(b) Produced water treatment plant upsets, which increase oil content in the discharged water by 2 to 4 times, increase the total loading of oil to the sea by an unknown amount which is expected to be small. The data on frequency of occurrence and duration do not allow quantitative estimates. (Chapter 4, Section 1.1.1)

(c) Ballast water containing 10 mg/L crude oil constituents, of which 5-9 mg/L are aromatic hydrocarbons, is not an important waste source if segregated-ballast tankers are used. The need to treat the water by using gas flotation or plate interceptors and for discharging the occasional load of crude-oil contaminated ballast water (caused by tank cross-contamination when oil is transferred between tanks during emergency situations) results in low loadings of aromatic hydrocarbons to the sea. Aromatic hydrocarbon concentrations in undiluted ballast water may be toxic and rapid dilution is essential. (Chapter 2, Section 3.3.1; Chapter 4, Section 1.1.2; Chapter 5, Section 3)

(d) Storage displacement water containing a maximum of 10 mg/L crude oil constituents, is discharged to the sea surface following treatment by plate interceptor. The loading of aromatic hydrocarbons to the sea from this source is low because only a small portion of the storage displacement water near the oil-water interface is contaminated with oil, and the aromatic content of the oil in the displacement water is low. (Chapter 2, Section 3.3.3; Chapter 4, Section 1.1.2)

1.2 Conclusions: Refined Oils

(a) Diesel oil adhering to discharged cuttings during the use of conventional oil-base drilling mud systems contributes to the sea floor 100-300 tonnes per well of oil having an aromatic content of 25-30%. Many of the aromatic compounds are persistent in the marine environment and they accumulate in biota. Current cuttings cleaning systems reduce oil content to 10%-15% of the total cuttings discharged. Cuttings cleaning systems under development may reduce oil content to less than 1%.

Hauling oiled cuttings to shore is an alternative to ocean discharge but presents problems of land disposal. (Chapter 2, Section 2.3.4; Chapter 3, Sections 1.0 and 2.2; Chapter 4, Sections 1.2.2 and 2.2; Chapter 8, Table 8-14)

(b) The diesel oil content of oil-base drilling fluids is typically 30%, of which 25-30% is aromatic hydrocarbon. These fluids are not discharged to the sea. Current practice is to haul the fluids to shore for re-use. Incineration of the oil and sea surface discharge of the ash is an alternative practice. (Chapter 2, Section 2.3.3; Chapter 4, Section 1.2.2)

(c) Diesel oil is added occasionally to water-base drilling muds when downhole problems are encountered. This spotting or lubricating oil may result in 2-5% diesel oil content in a portion of the drilling fluid and oil contamination of the drill cuttings. The contaminated fluid and cuttings are commonly separated from the solids control system for haulage to shore, although a portion is discharged to the sea providing an input of aromatic hydrocarbons to the marine environment. (Chapter 2, Section 2.3.1)

(d) Paraffin oil adhering to cuttings during the use of low-aromatic, oil-base drilling mud systems contributes to the sea floor approximately 50-200 tonnes per well of oil having an aromatic content of approximately 15%. These aromatic hydrocarbons are principally three-ringed and higher and are persistent in the marine environment. Alternative operating practices to reduce aromatic hydrocarbon release are: the use of new generation cuttings cleaners to reduce the oil content of cuttings; limiting the aromatic content of the paraffin oil base; and, haulage of cuttings to shore. (Chapter 2, Sections 2.3.3 and 2.3.4; Chapter 4, Sections 1.2.2 and 2.2)

(e) Lubricating, hydraulic and other refined oils in deck drainage discharges can be limited by good management practice such as collection through drains into sumps for recovery. These oils are otherwise washed overboard during rain and deck washings. (Chapter 2, Section 5; Chapter 4, Section 1.1.3)

1.3 Conclusions: Persistent Chemicals and Chemicals Which Do Not Occur in Nature

(a) A large number of manufactured chemical substances are used in offshore production operations, many of which are ultimately discharged with one of the normal wastes. Some of these chemicals are toxic to marine organisms or persistent in marine ecosystems. (Chapter 2, Sections 1.3, 2.3.1, 3.3.1, 6.0 and 8.0; Chapter 5, Section 6.)

(b) Biocides such as various aldehydes and quaternary amines are used in drilling muds; completion fluids and injection water; and in produced water and ballast water treatment systems. Chlorinated hydrocarbons, particularly pentachlorophenols, are now prohibited in many offshore producing regions. (As above)

(c) Surfactants, dispersants and detergents, in some cases including aromatic solvents, are ingredients in formulations which are used to wash decks; to clean oiled cuttings; to treat produced water and ballast water; and in drilling mud. They are discharged directly to the sea with the various effluents. (As above)

(d) Other organic chemicals used for corrosion inhibition, scale inhibition and many other purposes also are discharged to the sea. (As above)

(e) Chemical use and discharge offshore, particularly of persistent or highly toxic chemicals, require control. Control can be achieved through a variety of management and regulatory practices including prohibition, listing of approved chemicals and reporting of offshore chemical use by operators. (Chapter 6, Section 3.)

(f) Use and discharge of halogenated hydrocarbons, pentachlorophenols in particular, are prohibited at offshore oil and gas production facilities in the U.S., in accordance with the London Dumping Convention. (Chapter 6, Table 6-1))

1.4 Conclusions: Metals

(a) Drilling fluid compounds, in the order barite, chrome lignosulphonate and ferrochrome lignosulphonate, clays and minor additives are the principal sources of metal discharges from offshore development and production operations. Local accumulation (up to approximately one km from the platform) of mercury, cadmium, chromium and lead occurs in sediments and epifauna adjacent to drilling locations. (Chapter 2, Section 2.3.1; Chapter 5, Section 2.1.4)

(b) Loadings of metals from drilling are predicted to be about the same as or well below natural loadings in Canadian offshore areas except for the Scotian Shelf where the loading of cadmium and lead from production waste discharges is predicted to exceed natural loadings. (Chapter 8, Section 3.1.1)

(c) Treatment of drilling wastes to remove metals is not practical nor is it necessary. Control of metal discharges and reduction in metal loadings to the sea and sea floor can best be achieved by:

(i) screening sources of barite to eliminate those which are highly contaminated, particularly with mercury and cadmium;

(ii) the substitution of low-metal-content mud additives for those containing higher concentrations, such as ferrochrome lignosulphonate in the place of chrome lignosulphonate; and

(iii) prohibition of certain mud additives.
(Chapter 2, Section 2.3.1; Chapter 5, Section 2.1.4; Chapter 6, Section 3.)

(d) Produced water contains trace concentrations of zinc (0.2 mg/L) and in some cases lower concentrations of lead and nickel (0.1 mg/L) and cadmium and chromium (0.03 mg/L). Loadings of these metals from produced water discharges to the sea are low compared to natural flux rates. Produced water containing significantly higher concentrations of metals has been encountered at some production fields. In a number of cases, injection of produced water into a formation has been practised. (Chapter 2, Section 1.4; Chapter 8, Section 3.2)

(e) Mercury and cadmium compounds, are proscribed under the London Dumping Convention and are controlled in the U.K. through identification and screening of content in offshore production chemicals. (Chapter 6, Table 6-1 and Section 3.)

1.5 Conclusions: Waste Discharges of Limited Significance (Non-Issues)

The following wastes have been evaluated as having limited significance in the three Canadian offshore regions. These conclusions are based on the review of waste characteristics (Chapter 2), and the evaluation of treatment technologies and disposal methods and their application to Canada (Chapters 3, 4 and 7). The rationale for the first eight wastes is presented in Chapter 8, Table 8-15. The rationale for the last four wastes in the list is that limited or no discharge occurs and little or no contaminants are contained in these wastes.

- Cuttings from drilling operations utilizing water-base drilling fluids
- Well completion and workover fluids
- BOP control fluid
- Well cement
- Produced sand
- Treated sanitary waste and untreated domestic waste
- Gas and oil processing wastes (except certain persistent or highly toxic chemicals)
- Tanker and platform ballast water (assuming vessels with segreated ballast tanks)
- Slop oil
- Desalination waste
- Cooling water
- Fire control system test water

2.0 Conclusions Regarding Discharge Regulations

Conclusions have been made about appropriate regulatory approaches, the basis for control objectives and permit conditions, and substances which may be regulated at offshore production facilities. These conclusions are based on a synthesis of legislation and regulations in existing producing areas and the evaluation of environmentally significant wastes.

2.1 Regulatory Approach

(a) Pollution Control Objectives that apply to the entire Offshore Oil and Gas Production Industry can provide a good basis for environmental regulation, if well-formulated. These objectives should incorporate general principles for (i) marine environmental quality; (ii) adoption of pollution control technology and operational practices; (iii) specific maximum discharge limits for certain substances and a limited number of waste sources; and (iv) prohibition of discharge for a small number of highly toxic and persistent substances.

(b) Such objectives can be applied to each offshore producing region by the issuance of General Permits covering all operators in each region. Site-specific (platform-specific) approvals of waste treatment and disposal system design and proposed operational practices can supplement the General Permits.

(c) The General Permit conditions are based on the important biological resources and oceanographic conditions of the region, and the geological conditions which determine the nature of the hydrocarbons and how they are produced. General Permits can implement Offshore Production Pollution Control Objectives, applying their specific restrictions, modified where appropriate to account for regional conditions and the necessity to protect important biological resources. Waste treatment and disposal system technologies are generally not specified in these objectives, but are left to the discretion of the operator with the stipulation that they achieve certain levels of performance.

(d) The Pollution Control Objectives and General Permits can be developed for and applied to development drilling discharges and production waste discharges.

2.2 Basis for Objectives and Permit Conditions

(a) Waste discharge objectives for the offshore production industry and specific permit conditions can be based on the discharge level (concentration or loading) which is the lesser (more stringent) of:

- the level having a negative environmental effect which is judged to be important

or

- the level that can be achieved by the application of the Best Practical Control Technology

(b) Loading rate rather than effluent concentration is a more relevant measure of environmental effect to use for controlling waste discharges. No acutely toxic concentrations of whole wastes or individual constituents have been identified in offshore production discharges, after initial dilution. If a long-term accumulation of a contaminant can be predicted to result in an environmentally significant effect for a specified loading rate, then a restriction on loading of that substance to the sea can be specified, based on a maximum discharge concentration and maximum discharge flow rate.

(c) Pollution Control Objectives for the offshore producing industry can be established on the basis of Best Practical Control Technology (BPCT). If the evaluation of environmental effect made to establish General Permit conditions for a region results in BPCT being insufficient to prevent an environmentally significant effect, alternative treatment technology or management practices should be applied to the substance or discharge in question.[1]

2.3 Substances and Wastes to be Regulated

(a) It is concluded that the following substances and waste discharges may require regulation:

- total oil (kg/d) in:
  - produced water
  - ballast water
  - storage displacement water
  - oily cuttings
- total aromatic hydrocarbons (kg/d) in:
  - produced water
  - ballast water
  - oily cuttings

(b) Total oil is best measured by infrared (IR) spectrophotometry because this technique is effective on all types of offshore platforms; allows continuous measurement; allows a long-term permanent record to be made; and allows determination of specific constituents.

(c) Total aromatic hydrocarbon content is best measured by U.V. fluorescence spectrophotometry because it is specific to aromatic content; can be operated on all types of platforms; and allows continuous measurement.

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[1] An example of this situation may be the discharge of oily cuttings from the use of oil-base mud systems. The environmental effect of subsurface disposal may be shown to be unacceptable. Alternatives are development of cuttings cleaners which further reduce oil content; hauling of oily cuttings to shore; and prohibition of oil-base mud system use offshore.

(d) The nature, frequency and duration of treatment plant upsets must be taken into account in the regulation of oily discharges so as to limit total loading of oil and to prevent unreasonable hardship to offshore operators. There are insufficient data to formulate a specific conclusion.

(e) The use and discharge of persistent chemicals and those which do not occur in nature are regulated at offshore oil field development and production facilities in some jurisdictions. Naturally occurring substances used in large quantities offshore and known to contain potential contaminants, such as cadmium and mercury in barite, can be included.

(f) Alternative approaches for regulation of chemicals include the following:

- monitoring/reporting of offshore use;
- screening of sources of supply for major substances which are known to be occasional contaminants;
- specification of approved generic drilling fluids;
- chemical identification (by the supplier/user) of compounds used offshore;
- application of a list of approved substances; and
- prohibition of offshore use of certain substances.

(g) Specification of Best Practical Control Technology is a more suitable basis for controlling sanitary waste discharges than specification of discharge limits. This level of treatment may not be necessary in open sea offshore areas but may be required for shorebase or nearshore coastal installations.

(h) Specific management (operating) practices may be used in General Permits for oily processing wastes and deck drainage to limit discharges of refined oils.

(i) The offshore discharge of oil-base muds is prohibited in all jurisdictions reviewed.

3.0 Information Deficiencies Limiting Environmentally Sound Offshore Development and Regulation in Canada

3.1 Waste Characteristics

(a) Little is known of formation water characteristics in the three Canadian offshore regions and for specific fields under consideration for development (both major composition and trace metal and hydrocarbon constituents). The characteristics of formation water, once on surface as produced water, affect the treatment of this waste stream. This has implications for facility design and operation, establishment of regulations and prediction of environmental effects. The unreliability of much of the heavy metal data in the produced water literature, and the lack of data on aromatic content of produced water in the North Sea restrict estimation of produced water characteristics in Canadian offshore areas. Produced water characteristics are also site-specific in nature.

The aromatic content of produced water following breakthrough of injection water is also not documented in the literature.

(b) The characteristics of minor wastes such as deck drainage and slugs of completion fluids and workover fluids which pass through the produced water system are not well-documented in the literature nor in platform monitoring results. This is not a serious deficiency because these wastes are not environmentally significant.

(c) Few studies have considered the level of crude-oil contamination of cuttings originating from development wells passing through hydrocarbon-bearing formations.

3.2 Treatment and Disposal Technology

(a) The effectiveness of oily water treatment systems in removing aromatic hydrocarbons has not been well-documented for offshore production facilities. This information is necessary to determine methods for limiting aromatic hydrocarbon discharges to offshore areas.

(b) Information on the continuous performance of oily water treatment equipment at offshore production facilities is lacking in the available literature. It is necessary to determine the characteristics, and effects on effluent quality, of treatment plant upsets.

(c) The effects of cold temperatures, ice conditions and other factors inherent in Canadian offshore regions on the performance of production platform waste treatment systems have not been evaluated to date.

(d) The costs of applying existing treatment and disposal technologies to Canadian offshore areas have not been evaluated to date.

3.3 Environmental Fate

(a) Data on the transport of sediments and location of sediment sinks for future offshore producing areas are insufficient to predict the implications of contaminant loadings or to allow adequate comparison with natural flux rates. Such data would be required for the setting of discharge limits based on environmental effect.

(b) The regional data base for North Atlantic oceanographic processes, including areas of future offshore oil and gas production, is poor and inadequate to predict fate and effects of discharged wastes.

3.4 Environmental Effects and Monitoring

(a) The lack of time-series measurements of background levels of metals and aromatic hydrocarbons in sea water and sediments, and of benthic community composition, abundance and tissue contaminant levels prevents the determination of natural variation as a benchmark for future monitoring work.

(b) Few studies in North America have addressed the effects of the discharge of cuttings from oil-base mud systems. A significant portion of the work done to date, in the North Sea, was not available for use in this evaluation. However, a number of North Sea study results will be released in the fall of 1983. This limitation inhibits the making of sound decisions on the use of oil-base muds in Canadian offshore areas.

(c) The available literature (world-wide) and work done to date in Canada provide inadequate data on the effects of formation water (and future produced water) on Beaufort Sea and North Atlantic fish and invertebrate species.

(d) The laboratory and field studies which have examined the bioaccumulation of metals and aromatics in invertebrate tissue in the vicinity of offshore production platforms are not statistically conclusive. They lack results on field depuration rates of these potential contaminants near platforms.

(e) The results of recent North Sea studies on the effect of offshore production platforms on infaunal invertebrates were not available in time for inclusion in this report. No studies have been conducted on infaunal invertebrates around Gulf of Mexico production platforms.

(f) The sensitivity of juvenile forms of marine fish and invertebrates to produced water has been inadequately studied and documented.

4.0 Recommendations for Future Research in Canada

4.1 Waste Characteristics

(a) Formation water has been analysed to a limited degree during offshore exploration in Canadian waters. Evaluation of these results and collection and analysis of additional samples will aid regional assessment of the potential effect of produced water discharges and will allow the setting of appropriate discharge standards and the design of treatment systems for produced water.

4.2 Treatment and Disposal Technology

(a) A detailed evaluation of the cause, nature, frequency and duration of offshore platform oily water treatment system upsets will provide information on effluent quality during upsets and on the increase in loading of total oil and aromatic hydrocarbons to the sea. Such an evaluation could be conducted by a detailed review of past studies and of operating records for a number of recently constructed platforms employing the Best Practical Control Technology. These results are necessary to form reasonable and effective regulations or permit conditions for addressing treatment plant upset conditions.

(b) An assessment of the application to Canadian conditions and regions of disposal practices currently used in other regions, such as surface discharge, subsea disposal, hauling to shore for disposal in landfills and other methods is required. Specific Canadian conditions, particularly ice-covered seas and permafrost, may affect the utility, effectiveness and desirability of applying these techniques to Canadian areas. Such an assessment should cover the implications of land (onshore) disposal of wastes.

(c) An evaluation of the costs for levels of treatment (Best Practical, Best Available, State-of-the-Art) applied to offshore Canadian areas is required for two wastes, oily water and oiled cuttings, in order to assist the industry in its selection of appropriate waste treatment facilities and the government in establishing regulations and permit conditions for offshore production.

(d) A cost/benefit analysis of alternatives for handling (treating, disposing) and regulating oily cuttings is necessary so that decisions can be made on the use of oil-base mud systems in Canadian waters. The current Best Practical Control Technology (conventional cuttings cleaning to 10-15% oil) is not adequate.

(e) An assessment of the effectiveness of oily water treatment systems in removing aromatic compounds from produced water will help government to establish reasonable permissible limits for aromatic hydrocarbon discharges. Current Best Practical Control Technology is designed to remove free oil, not aromatics.

4.3 Environmental Fate and Effects

(a) Modelling of sediment transport in the three Canadian regions and specific sites of future production will provide information on transport rates and frequency of sediment reworking. These transport processes have implications for habitat modification and accumulation of contaminants from waste discharges.

(b) Evaluation of the long-term accumulation of aromatic hydrocarbons in areas of limited circulation, and where there are many large sources of loading, (many platforms with high produced water discharge rates) is a long-term research requirement for Canadian offshore production.

(c) The influence of ice cover on the dispersion and effects of platform discharges, particularly produced water, in shallow waters will assist design of discharge systems and formulation of appropriate permissible limits.

(d) A detailed evaluation of the effects of oil-base mud systems used in oil and gas field development is necessary to allow decisions on their use in Canadian waters. This evaluation would include a review of studies conducted in the North Sea (at Statfjord, Murchison, Beatrice, Beryl and other fields) which were not available for this report, further toxicity testing of oily cuttings and assessment of the ecological effects of oily cuttings discharges in Canadian waters. This work could best be done in conjunction with recommendation 4.2(d).

(e) There is limited need for further bioassays of whole drilling mud. Emphasis should be on testing new additives and screening drilling mud additives and other chemicals.

4.4 Offshore Regulation

(a) A detailed listing and evaluation of chemicals used in offshore development and production operations is necessary. This should include determination of chemical formulations, toxicity and persistence. A catalogue of approved or prohibited substances for Canadian offshore use should be developed.

(b) An evaluation of regulatory means for addressing treatment plant upsets (see 4.2(a)) is necessary because, in the view of offshore operators, the regulations are inadequate and sometimes unreasonable in other parts of the world.

5.0 Approaches to Offshore Monitoring in Canada

A detailed discussion and specific recommendations on the topic of offshore monitoring for oil and gas production platforms is beyond the scope of this study. A list of guidelines for the design and conduct of such programs is presented below, based on the experience gained from the reviews of literature and evaluations contained in this report.

Surveillance:	repeated measurement of parameters to determine compliance with a pre-set level (performance or regulatory)
Monitoring:	repeated measurement of parameters to determine the nature and probable cause of change in relation to natural variability; examines a hypothesis.

(a) Waste discharge (effluent) sampling and analysis, for regulation at the source or maintenance of a pre-determined level of performance, can be considered surveillance.

(b) Sampling and analysis of the receiving environment (chemical and biological) are considered as "monitoring" as it is very difficult to regulate marine discharges by sampling the receiving environment.

(c) The focus of biological community monitoring should be on infauna (sessile) organisms and epifauna along with the sediments in which they live rather than on water-column organisms and water sampling.

(d) Well-designed, parameter-specific monitoring programs are required to allow comparison between loadings of contaminants from platform discharges and natural fluxes of contaminants within a region.

(e) Field measurements and modelling of transport processes for future Canadian producing regions are necessary for the design of long-term monitoring programs.

(f) Indigenous marine species should be used for bioassay testing of wastes and chemicals that are expected to be discharged from Canadian offshore operations.

(g) Greater emphasis is needed on field monitoring and research that is ecologically relevant to the impacts of wastes on the productivity, energetics and structure of communities adjacent to platforms. There is too much current emphasis on sublethal laboratory testing which is not related to field population performance.

(h) Monitoring contaminant levels such as metals and hydrocarbons in tissue needs to be better correlated with threshold levels for effects on marine organisms.

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TABLE OF CONVERSIONS

1 cubic metre (m^3) = 1000 litres (L)
= 35.3 cubic feet (ft^3)
= 6.29 barrel (U.S. bbl)
= 264 gallons (U.S. gal)
= 220 gallons (Imp. gal)

1 barrel (U.S. bbl) = 159 L
= 0.159 m^3

1 ft = 0.305 m
1 ft^2 = 0.093 m^2
1 ft^3 = 0.028 m^3

1 gram/cubic centimetre (g/cm^3) = 8.35 pounds/gallon (lb/U.S. gal)

1 kilogram (kg) = 2.2 lb
1 kg/m^2 = 0.205 lb/ft^2
1 L/s = 15.85 US gpm
1 milligram (mg) = 0.001 kg

1 mg/L = 1 part per million (ppm)

$ Canadian = $ 0.8 U.S.

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CHAPTER 1

INTRODUCTION

1.0 Report Objectives

This report contains an evaluation of wastes discharged from existing offshore oil and gas production platforms. It also includes an assessment of existing practices as they affect Canadian offshore regions where future production is anticipated. The specific objectives of the report are to provide:

(1) A summary of production waste characteristics, volumes and disposal practices for existing offshore oil and gas production fields;

(2) A comparison of existing and state-of-the-art treatment technologies and disposal practices used for offshore oil and gas production wastes, including their cost and effectiveness;

(3) A review of known and potential adverse effects on the marine environment resulting from wastes discharged from offshore oil and gas production platforms;

(4) An assessment of the relative importance and significance of future oil and gas production waste discharges in Canadian offshore waters;

(5) An assessment of deficiencies in existing data which limit their application to the Canadian situation, and recommendations for future research priorities.

2.0 Report Scope

The report examines wastes which are generated at offshore oil and gas production platforms and discharged on-site or transported to shore for treatment and disposal. Exploration wastes and wastes from construction and testing of facilities are not discussed in the report. Production wastes are defined as wastes generated during the drilling and completion of development wells, and all liquid wastes generated during normal oil and gas extraction and primary processing.

Emergency situations such as oil or chemical spills and chronic spills from offshore platforms are outside the scope of this report, as are all air emissions. The waste treatment and disposal technology assessments presented are based on existing technology or that under development. No primary design work has been done for the purposes of this report.

The review of literature and industry practice deals with three U.S. offshore producing regions: Gulf of Mexico, California coast and Cook Inlet, Alaska; and, the U.K. and Norwegian sectors of the North Sea producing fields. The results of this review and evaluation have been applied to three Canadian offshore regions with potential for production of oil and gas; namely, the Scotian Shelf, Grand Banks and Beaufort Sea. Production scenarios given for each region are typical of world-scale offshore production facilities and are based on a combination of available government and industry estimates and current world practice. Information available from the industry was not sufficient to develop site-specific scenarios which closely match current production plans.

3.0 Report Organization and Approach

The report has four components:

	(1)	Review and evaluation of waste characteristics, disposal practices and treatment technology;	Chapters 2, 3, 4
	(2)	Review of biological effects and marine discharge regulations;	Chapters 5, 6
	(3)	Definition of typical offshore production scenarios and waste discharge estimates, determination of zones of influence for each region and evaluation of biological concerns;	Chapters 7, 8
and	(4)	Conclusions and recommendations	Chapter 9

Chapters 2-6 have been drawn from industry and government reports, the scientific literature, industry and government monitoring data, major reviews of wastes and biological effects, trade journals, manufacturers' specifications and brochures, and interviews with senior staff from the oil industry and regulatory agencies. The results of this investigation are presented as being typical of world practice and known effects, rather than as detailed literature reviews, and are organized by offshore producing region, where appropriate. In some cases, key data have been abstracted or adapted from relevant literature sources and properly acknowledged. In other cases, a large number of information sources have been synthesized to present typical descriptions of waste characteristics, treatment and disposal practices and biological effects.

A list of the literature and personal communications cited follows each chapter. The nature of the information presented, particularly for current offshore industry practice which is seldom documented, has resulted in personal communications, through interviews and correspondence, being an important source of information in the report.

CHAPTER 2

CHARACTERISTICS OF EXISTING OFFSHORE PRODUCTION WASTES

The major discharges from offshore oil and gas production activities are:

- produced water
- drilling fluids and cuttings
- ballast water
- storage displacement water

This assessment is based on the volumes of waste discharged to the ocean and the amount of contaminants (hydrocarbons, heavy metals and exotic additives) associated with these discharges, and the importance which has been placed on these waste discharges by government regulatory agencies, industry environmental scientists and researchers in general.

Minor discharges from offshore production are:

- produced sand
- deck drainage
- well completion and workover fluids
- miscellaneous well fluids (cement, BOP fluid)
- sanitary and domestic wastes
- gas and oil processing wastes
- miscellaneous discharges
    - slop oil
    - cooling water
    - desalination brine
    - fire control system test water

These minor wastes are sometimes mingled with one of the four major discharges; in all cases waste volumes and inputs of contaminants are small compared with the other sources.

1.0 Produced Water

1.1 Introduction

Formation water, not to be confused with produced water, is found in the rock formation, along with crude oil and gas, before it is brought to the surface. It is difficult to accurately describe its chemical composition because formation water is under pressure and in equilibrium with crude oil and gas in the formation.

Produced water (also known as production water or produced brine) is the total water discharged from the oil and gas extraction process (Oldham 1982). It comprises the formation water, which has been brought to the surface with the oil and gas, injection water (water pumped into the ground from the surface to assist with oil recovery from the reservoir), if this water has broken through into the oil formation, and various chemicals added during the oil/water separation process. Produced water comprises dissolved, emulsified and particulate crude oil constituents, natural and added salts, organic chemicals, solids and trace metals.

A comparison of typical produced water characteristics for four offshore producing regions of the world indicates that discharge rates, chemical composition, handling practices and analytical methods used for monitoring differ widely within and between regions (Table 2-1).

1.2 Discharge Rates

Table 2-2 is a summary of produced water discharge rates at oil producing platforms for four offshore producing regions.

The rate of discharge for produced water varies:

(i) from well-to-well over a given field;

(ii) from field-to-field in a given region; and

(iii) with time over the life of a producing field.

The lowest produced water discharge rates generally occur during the early stages of production or in fields where most of the produced water is reinjected. Higher rates of discharge tend to occur with older fields. Some North Sea fields, one example being Claymore, have had high levels of produced water early in their life.

TABLE 2-1

COMPARISON OF PRODUCED WATER FROM DIFFERENT OFFSHORE REGIONS

	GULF OF MEXICO		COASTAL CALIFORNIA		COOK INLET		NORTH SEA	
	Range	Typical Value	Range	Typical Value	Range	Typical Value	Range	Typical Value
Discharge Rate (m^3/d)	16-40,000	1,000	40-4,000	1,200	200-17,000	10,000	400-10,000	2,000
Major Constituents								
pH	5.8-7.6	6.5	-	6.5	6-9	-	-	-
TDS (mg/L)	6,000-300,000	110,000	20,000-40,000	25,000	-	-	35,000-130,000	-
TSS (mg/L)	20-90	40	1-60	-	-	-	-	1
Cl^- (mg/L)	16,000-170,000	60,000	17,000-21,000	-	-	-	-	30,000
SO_4^{-2} (mg/L)	0-70	0	50-60	58	-	-	0-400*	0
TOC (mg/L)	70-650	450	-	-	190-435	300	-	200
oil (GR) (mg/L)	2-400	40	10-360	15	0-23	10	-	-
oil (IR) (mg/L)	15-105	45	-	-	-	-	6-250	40
benzene (mg/L)	0.2-2.0	1.5	<1	-	3.4-5.9	5.0	-	-
phenol (mg/L)	0.2-3.4	0.5	0.2-0.7	0.46	-	-	-	-
cadmium (mg/L)	0.02-0.2	0.03	0.02-0.2	-	-	-	-	-
chromium (mg/L)	0.06-0.4	0.1	0.001-0.06	0.02	-	-	-	-
zinc (mg/L)	0.03-0.6	0.1	0.05-3.2	-	-	-	-	-
Handling Practice	Oil separators (skim tank) and dissolved or dispersed gas flotation, discharge overboard or down skim pile to mid-depth		Transferred to shore by pipeline; shore treatment and injection into formation		Transferred to shore for treatment (air flotation) and discharge to coastal waters		Oil separators (skim tank, plate separator) followed by dissolved air flotation and discharge down skim pile to mid-depth	
Analytical Method for Oil Content	Gravimetric oil, Standard EPA method**		Gravimetric oil, Standard EPA method		Gravimetric oil, Standard EPA method		Infra-red (IR)	

NOTE: Oil content values are for platforms using current Best Practical Control Technology; in most cases this involves primary gravity separation and gas flotation.

* Normally 0; 400 mg/L if breakthrough of injection water occurs.

** EPA, 1979. Methods for chemical analysis of water and wastes. Environmental monitoring and support laboratory, Environmental Research Centre, Cincinnatti, Ohio.

Note: Method detects "oil and grease".

TABLE 2-2

OFFSHORE PRODUCED WATER DISCHARGE RATES
(Oil and Oil/Gas Production Platforms)

LOCATION	Typical Produced Water Discharge Rates m^3/d	PRODUCED WATER DISCHARGE RATE $\bar{X}$ m^3/d	Median m^3/d	Range m^3/d	REFERENCES	
Gulf of Mexico	8-16,000				Melligner et al. 1979	
		-	-	656-1,600	Goodman & Troake 1982 (1 platform)	
		884	664	31-2,709	Jackson et al. 1982 (10 platforms)	
		95	-	-	Middleditch et al. 1978	
		1,877	552	56-24,000	Mors et al. 1982 (24 platforms)	
	3,800-38,000	2,400	-	40-40,000	Maer 1973 (25 platforms)	
		514	440	56-1,120	Myers et al. 1975 (4 platforms)	
California		1,280	1,026	38-3,800	Shell 1981	
		1,072	-	736-1,280	Myers et al. 1975 (3 platforms)	
Cook Inlet		504	547	2,272 (max)	U.S. EPA 1982a	(Granite Point)
		105	105	25-204		(Platform Bruce)*
		9,310	9,429	10,978 (max)		(Trading Bay)
		1,270	-	-	Lysyj 1982	(Kenai)
		1,750	-	-		(Dillon)
North Sea	24,000				Goodman & Troake 1982	
		120	-	-	E & P Forum 1982a	
		10,160	1,500	400-60,000	Schreiner 1980 (7 fields)**	
		280***	-	-	Moore 1980	(Piper and Claymore Fields)
		10,000****	-	-	pers. comm. Johnston	(Piper and Claymore Fields)

Note: All values are per platform, except those for the North Sea which are for one or more field.

* Produced water and deck drainage comingled.

** Maximum permitted discharge including produced water, deck drainage and storage displacement water.

*** At start up.

**** Several years after start up.

Data were not available on well-to-well variation. Such variation depends on well location within the field, and fluid production capacity of the well.

Field-to-field variation within a region is large. Table 2-3 shows this for Gulf of Mexico fields (offshore Texas and Louisiana). The largest number of platforms (discharge points) have relatively low discharge rates, but the range is large.

Produced water flow rates fluctuate daily and change over time (over the life of the field) (pers. comm. Caudle).

Short-Term	**Mid-Term**	**Long-Term**
daily fluctuations result from varying production conditions (some wells producing, others not)	discharge rates change as wells worked over and production methods change	high rates occur when water inflow to produced fluid increases

Produced water discharge rates for platforms producing only gas can be expected to be significantly lower than those from oil producing platforms. A typical value is 6 m^3 water/million m^3 gas (1 bbl/million ft^3). The Frigg gas field in the North Sea, which produces 40 million m^3/d gas, discharges approximately 50 m^3/d produced water including processing wastes (Schreiner 1980).

Produced water discharge rates for platforms in the Gulf of Mexico producing gas only had the following statistics for one study of 6 platforms (Mors et al. 1982).

Range	21-321	m^3/d
Mean	153	m^3/d
Median	147	m^3/d

There is no simple correlation between produced water discharge rate and oil production rate because the rate of discharge of produced water varies greatly from region to region and with the age of the field.

Early in a field life the ratio of produced water: produced oil is usually very low (about 0.01:1). As the field matures, this ratio may rise to 0.3:1 and up to 1:1 (UK DOE 1976). For some Gulf of Mexico platforms, the ratio is as high as 5:1. A 1978 produced water:oil estimate for all offshore California production wells was 5.7:1 (produced water represented 85% of total fluid production) (Langer 1981). A similar 1974 estimate for all offshore Texas production wells was 2.8:1 (produced

TABLE 2-3

RANGE OF GULF OF MEXICO PRODUCED WATER DISCHARGES

DISCHARGE (m^3/d)	NUMBER OF DISCHARGE POINTS Coastal	Offshore
160	434	393
320	146	132
800	115	71
1,600	70	36
6,400	40	0

Adapted from: U.S. Environmental Protection Agency. 1977.

water represented 74% of total fluids) (Langer 1981). While high water:oil ratios are relatively common in old Gulf of Mexico fields, such high ratios generally tend to make producing fields uneconomic; consequently the ratio seldom exceeds 1:1 to 2:1.

At some North Sea fields, produced water volumes were underestimated prior to production start up and have increased faster than expected. Breakthrough of injection water has been responsible for this in some cases (pers. comm. Johnston).

Figure 2-1 shows a typical increase in produced water discharge rate over the life of an oil field.

1.3 Chemical Additives

The chemicals used in oil production are injected down the well with injection water, added to the oil or gas during treatment of the product on the platform or added to the oily water (produced water) separators to increase oil removal efficiency. While the chemicals added to the oil are generally soluble in the oil, a few mg/L, and in some cases considerably more, may become associated with the produced water (E+P Forum 1982a). When injection water breakthrough occurs, biocides may be present in produced water (pers. comm. Johnston). Dosage rates for chemical additives to the oily water separators are about 5-30 mg/L, depending on the chemical used (pers. comm. Caudle).

The wide range of chemical additives used during the various stages of oil production is shown in Table 2-4. Some of the chemicals which are used or have been used in offshore producing fields are highly toxic or persistent.

1.4 Composition

The constituents in produced water can be divided into five groups: (1) major constituents (anionic and cationic salt constituents, metal ions such as iron and manganese), (2) organic constituents (particulate and colloidal crude components such as paraffins and asphaltenes, and dissolved components such as aromatics), (3) trace metals, (4) additives and (5) suspended solids. Chemical additives have been discussed previously. Suspended solids will be addressed in the following section on produced sand. Particulate and colloidal oils are the only constituents which are significantly reduced by the oily water separation systems commonly used offshore; dissolved aromatics are reduced to a lesser extent. Treatment does not reduce the concentrations of salts and dissolved metals in produced water.

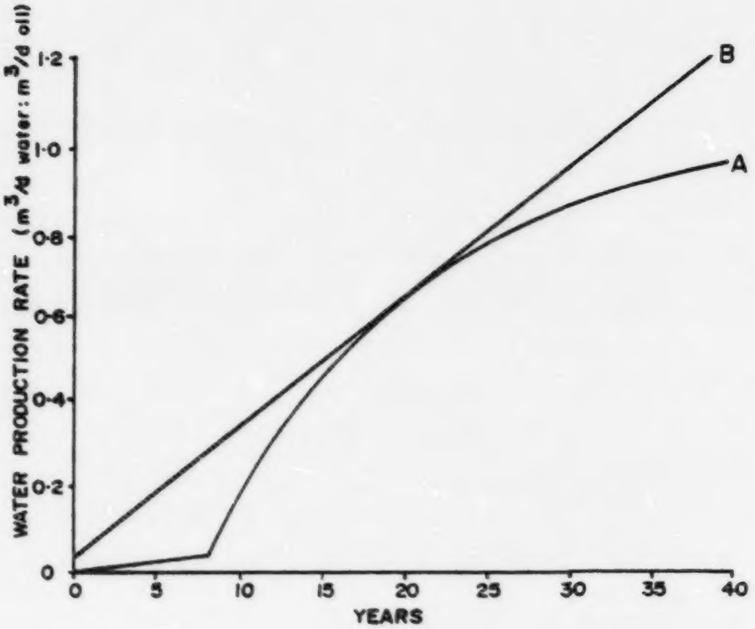

FIGURE 2·1 TYPICAL CHANGE IN PRODUCED WATER DISCHARGE OVER OIL FIELD LIFE (AS A FUNCTION OF INITIAL OIL PRODUCTION RATE)

(SOURCE: (A) ADAPTED FROM SHAWMOUNT MARTEC LIMITED, 1982
(B) PERS. COMM. JOHNSTON)

TABLE 2-4

CHEMICAL ADDITIVES USED IN OIL AND GAS PRODUCTION

STAGE	PURPOSE	DOSAGE	COMMON CHEMICALS	FATE
Water Injection	biocide	20-100mg/L	chlorine, aldehydes, quaternary amines, pentachlorophenol*	lost to formation unless injection water breaks through into produced fluids; occurs for some fields, particularly as they age
	corrosion inhibitor		chromates, zinc phosphorus salts, mono-, di- and quaternary amines,	
	foam inhibitor		fatty acid soaps, phosphate esters	
	demulsifier	1-40mg/L	phosphate esters, quaternary amines, aromatic solvent, alcohol solvent	
Oil Processing	demulsifier	-	same as for water injection	some dissolution of chemical into oily water and discharged with treated produced water
	scale inhibitors	-	ethylene diamine tetraacetic acid (EDTA); sodium phosphates, carboxylmethyl-cellulose	
	wax deposition inhibitors and flow aids	100-200 mg/L	vinyl or acrylate copolymers (crystal modifiers); dispersants; detergents	
Gas Processing	dehydration	-	methanol, glycol (ethylene, di-ethylene, tri-ethylene)	minor loss of these chemicals into deck drainage system by leaks, drips
	oxygen scavenger	-	ammonium bisulphite, thiosulphates	
	acid gas scrubbing	-	monoethanolamine diethanolamine	
Oily Water Treatment	coagulant and flocculant	-	ferrous sulphate, aluminum sulphate, high molecular weight poly-electrolytes	discharged with treated produced water
	demulsifier	-	high molecular weight poly-electrolytes	

Sources: Maer 1975
pers. comm. Caudle
pers. comm. Williams
E+P Forum 1982a
UK DOE 1976
pers. comm. Johnston

* No longer in use.

The composition of produced water for four offshore producing regions is shown in Tables 2-5 to 2-9. Essentially all represent oil producing facilities. The values represent produced water effluent after treatment by air flotation or similar polishing unit in most cases. The analytical methods used to produce some of the results in Tables 2-5 to 2-9 are given in Table 2-10.

Total dissolved solids concentrations, comprising principally the major salt constituents, vary considerably among the produced water sources and regions. Some produced waters are relatively fresh (<10,000 mg/L salts) while others are relatively strong brines (>150,000 mg/L salts). Although sulphate values are usually near zero, if breakthrough of injection water occurs sulphate can be as high as 400 mg/L. In some cases in the U K North Sea, this has led to problems with scale formation resulting from coprecipitation of barium, strontium, radium, thorium and iron with the sulphate (pers. comm. Johnston).

The oil content of treated produced water is affected by the chemical content (inorganic and organic) of the untreated produced water, the type and efficiency of oil separation unit used on the platform, the concentration of dissolved oil in the produced water, fluctuations in flow rate and quality, and the presence of wastes such as deck drainage and spent acid in the produced water treatment system (pers. comm. Caudle, Berry, Burgbacher). Following treatment, produced water always contains some residual oil because soluble crude oil constituents and finely dispersed particulate oil cannot be efficiently removed by currently used gravity or gas flotation oily water treaters (pers. comm. Caudle 1982). The oil content of produced water following such treatment, however, is generally between 30 and 50 mg/L. Some U.K. results suggest that light aromatic compounds can form a large part of the total oil in produced water discharges (pers. comm. Johnston).

The effect of upset conditions on oil content of produced water and the causes of upsets are presented in Chapter 4, Section 1.1. Upsets can cause oil content in effluent to rise to levels between 100 and 400 mg/L.

A relatively small number of aromatic hydrocarbon compounds have been found consistently in produced water from the Gulf of Mexico, coastal California and Gulf of Alaska; these compounds were: benzene, toluene, ethylbenzene, 2,4-dimethylphenol, napththalene and phenol. A small number of other compounds have been identified (see Table 2-6), but only in one or two of a number of platforms sampled.

Samples of produced water were analysed for the full range of 129 U S EPA priority pollutants in two recent surveys (Radian Corp. 1982 and Lysyj 1982).

TABLE 2-5

GULF OF MEXICO PRODUCED WATER COMPOSITION - MAJOR CONSTITUENTS

PARAMETER	UNITS	REFERENCE 1			REFERENCE 2,6,3			REF. 4	REF. 5
		$\bar{X}$	Median	Range	$\bar{X}$	Median	Range	Range	Typical
Physical Properties									
- temperature	°C	38.1	39.2	22.6-48.2	20	20	20-21	-	-
- specific gravity		1.110	1.101	1.073-1.151	-	-	-	-	-
- surface tension	dynes/cm	63	62	57-68	-	-	-	-	-
Major Constituents									
- pH		6.6	6.6	6.2-7.1	6.45	6.35	5.82-7.60	-	-
- TDS	mg/L	129,950	114,000	80,500-203,00	102,172	107,353	11,273-199,313	169,000	-
- SS (or TSS)	mg/L	-	-	-	45	41	18-87	12-656	-
- Cl	mg/L	-	-	-	60,283	60,518	16,667-115,481	42,000-62,000	-
- SO_4	mg/L	-	-	-	9	0	0-69	-	300
- K	mg/L	-	-	-	-	-	-	-	-
- Sr	mg/L	-	-	-	-	-	-	-	85
- Fe (total)	mg/L	-	-	-	29	-	8-100 (Ref. 3)	-	-
- Mn	mg/L	-	-	-	-	-	-	-	4
Composite Organics									
- oil (GR)	mg/L	39.0	37.0	7.6-77	-	-	-	-	-
- oil (IR)	mg/L	56.9	43.5	15-106	-	-	-	-	-
- COD	mg/L	-	-	-	-	-	-	182-582	-
- BOD	mg/L	-	-	-	-	-	-	126-342	-
- TOC (TOC mgC/L)	mg/L	-	-	-	404	463	68-661 (Ref. 7)	-	

REFERENCES:

1 Jackson et al. 1981 (Ten offshore Louisiana platforms)
2 Myers et al. 1975 (Twenty-five Gulf Coast platforms)
3 U.S. EPA 1980
4 Train et al. 1976
5 Goodman and Troake 1982
6 Lysyj 1982 (Six Gulf Coast platforms)

TABLE 2-6

GULF OF MEXICO PRODUCED WATER COMPOSITION - TRACE CONSTITUENTS

PARAMETER	UNITS	REFERENCE 2		REFERENCE 3		REFERENCE 1,4		
		$\bar{X}$	Range	$\bar{X}$	Range	$\bar{X}$	Median	Range
Trace Organics								
- benzene	mg/L	3.5[a]	0.18 - 14.0	0.836	0.170 - 1.90	1.955	1.229	0.137 - 11.335 Ref.4
- toluene	mg/L	2.4[a]	0.16 - 7.95	2.074	0.770 - 3.30	-	-	-
- ethylbenzene	mg/L	0.23[a]	0.028 - 0.55	0.101	0.042 - 0.200	-	-	-
- naphthalene	mg/L	0.148[a]	0.018 - 0.300	0.027	0.012 - 0.0448	-	-	-
- phenol	mg/L	1.00[a]	0.20 - 3.40	0.486	0.018 - 0.840	2.203	0.808	0.108 - 20.812 Ref.4
- 2,4-dimethylphenol	mg/L	0.132[a]	0.016 - 0.570	-	-	-	-	-
- bis(2-ethylhexyl) phthalate	mg/L	0.028[a]	0.016 - 0.118	-	-	-	-	-
- di-n-butylphthalate	mg/L	0.010[b]	0.010 - 0.010	-	-	-	-	-
- benzo(a)pyrene	mg/L	0.016[b]	0.012 - 0.021	-	-	-	-	-
- 2,4-dinitrophenol	mg/L	0.127[c]	-	-	-	-	-	-
- fluorene	mg/L	0.017[c]	-	-	-	-	-	-
- phenanthrene	mg/L	0.236[c]	-	ND	ND	-	-	-
Trace Metals								
- Ag	mg/L	-	< 0.050 - < 0.087[d]	-	0.001 - 0.152[e]	-	-	< 0.01 - 0.1 Ref.1
- As	mg/L	-	-	-	< 0.005 - 0.05[e]	-	-	< 0.01 - <0.02 Ref.1
- Cd	mg/L	-	0.028 - < 0.044	-	< 0.025 - 0.056[f]	-	-	< 0.02 - 0.193 Ref.1
- Cr	mg/L	-	< 0.13 - < 0.25	0.260	< 0.059 - 0.390[f]	-	-	< 0.10 - 0.23 Ref.1
- Cu	mg/L	-	< 0.091 - 0.014	-	< 0.025 - 0.137[f]	-	-	< 0.10 - 0.38 Ref.1
- Hg	mg/L	-	-	-	< 0.0003 - < 0.001[e]	-	-	< 0.001 - 0.13 Ref.1
- Mn	mg/L	-	-	-	-	-	-	- Ref.1
- Ni	mg/L	-	0.13 - < 0.25	-	< 0.068 - 1.674[f]	-	-	< 0.10 - 0.44 Ref.1
- Pb	mg/L	-	< 0.50 - < 1.2	0.597	< 0.16 - 0.915[f]	-	-	< 0.01 - 0.22 Ref.1
- Zn	mg/L	0.131[d]	0.028 - 0.32	0.350	< 0.025 - 0.640[f]	-	-	0.10 - 0.27 Ref.1

NOTES:

a by GC-MS (gas chromatography-mas spectrometry); all values are averages of results derived by internal standard and isotope dilution determination.
b Detected at 2 platforms
c Detected at 1 platform
d By standard addition AAS (atomic absorption spectrometry)
e By flameless AAS
f By plasma emission spectrometry
g Detected in 3 of 6 platform effluents

ND not detectable at 1 µg/L

REFERENCES:

1. Train et al. 1976
2. Radian Corporation 1982 (Six Gulf Coast platforms)
3. Lysyj 1982 (Six Gulf Coast platforms)
4. Mors et al. 1982

TABLE 2-7

CALIFORNIA PRODUCED WATER COMPOSITION

PARAMETER	UNITS	REFERENCE 1		REFERENCE 2		REFERENCE 3	
		$\bar{X}$	Range	$\bar{X}$	Range	$\bar{X}$	Range
Major Constituents							
- pH						6.55	6.41 - 6.72
- Total dissolved solids	mg/L		21,700 - 40,400			21,638	20,000 - 25,000
- Suspended solids	mg/L		1 - 60			-	-
- Chloride	mg/L		17,230 - 21,000			-	-
- Sulphate	mg/L		- - -			57.5	53.0 - 60.0
- Nitrate	mg/L		- - -			0.15	0.00 - 0.31
- Phosphate	mg/L		- - -			0.04	0.00 - 0.10
- Ammonia	mg/L		- - -			24.0	16.0 - 28.0
Composite Organics							
- COD	mg/L	-	400 - 3,000	-	- -		
- BOD	mg/L		370 - 1,920	-	- -		
- Oil-GR	mg/L	20.1	56 - 359	27.1	3 - 74		
- cyanide	mg/L	< 0.02	0.0 - 0.004	-	- -		
Trace Organics[1]							
- benzene	mg/L						
- toluene	mg/L						
- xylenes/ethylbenzene	mg/L						
- ethylbenzene	mg/L						
- naphthalene	mg/L						
- phenolic compounds	mg/L	0.63	0.35 - 2.10	0.60	0.30 - 0.95	2.85	2.4 - 3.5
Trace Metals[2]							
- Ag	mg/L	0.030		-	< 0.01 - 0.028		
- As	mg/L		0.001 - 0.080	-	0.015 - 0.08		
- Cd	mg/L		0.020 - 0.18	0.07	0.006 - 0.20		
- Cr	mg/L		0.020 - 0.04	0.05	0.02 - 0.07		
- Cu	mg/L		0.050 - 0.116	0.04	< 0.005 - 0.12		
- Hg	mg/L		0.0005 - 0.002	-	< 0.0008 - < 0.002		
- Ni	mg/L		0.100 - 0.290	0.39	0.16 - 0.90		
- Pb	mg/L		0 - 0.280	-	0.040 - 0.380		
- Zn	mg/L		< 0.050 - 3.200	0.06	0.03 - < 0.200		

REFERENCES:

1 Train et al. 1976
2 U.S. EPA 1982b (Platforms Grace, Hillhouse, Hogan)
3 OOC 1975 (Platform Harry)

NOTES:

1. In EPA sampling, aromatic hydrocarbon levels at a number of California platforms were found at approximately same concentrations and composition as for Gulf of Mexico platforms (See Table 2-6). (pers. comm. Kirby)

2. Priority pollutant sampling at California platform by EPA has found only zinc to be present in all produced water samples, at a similar level to that found in Gulf of Mexico (see Table 2-6) (pers. comm. Kirby)

TABLE 2-8

COOK INLET PRODUCED WATER COMPOSITION

PARAMETER	UNITS	REFERENCE 1,2			REFERENCE 2			
		Platform A	Platform B	Platform C	Platform A		Platform B[3]	
		Aug	Aug	Aug	$\bar{X}$	Range	$\bar{X}$	Range
Physical Properties								
- temperature	°C	29	44	47	-	-	-	-
Major Constituents								
- pH		7.0	-	-	6.8	6.5-7.2	7.0	7.0
Composite Organics								
- TOC	mg/L	435	288	188	-	-	-	-
- Oil - GR	mg/L	8.1	-	-	9.4	8.3-19.0	20.1	2.3-105.8
Oil - IR	mg/L	-	-	-	-	-	-	-
- Total oil (calculated)	mg/L	10.2	10.9	10.2	-	-	-	-
Trace Organics[1]								
- Aliphatic hydrocarbons	mg/L	1.3	0.9	0.7	-	-	-	-
- Aromatic hydrocarbons	mg/L	5.6	9.3	10.2	-	-	-	-
- Benzene	mg/L	3.4	5.7	5.9	-	-	-	-
- Toluene	mg/L	1.6	2.6	3.1	-	-	-	-
- Xylenes	mg/L	0.6	1.0	1.2	-	-	-	-
Metals[2]								

REFERENCES:

1 Lysyj 1982. Platform A Trading Bay (onshore oil separation)
Platform B Kenai (onshore oil separation)
Platform C Dillon (offshore oil separation)

2 U.S. EPA 1982a.
Platform A Granite Point
Platform B Bruce

NOTES:

1 EPA sampling at Cook Inlet platforms has identified the same seven aromatic hydrocarbons commonly found in Gulf of Mexico sampling (see Table 2-6) at approximately twice the concentration for the sum of the constituents (pers. comm. Kirby)

2 EPA sampling at Cook Inlet platforms has identified only zinc as a consistent constituent of produced water (pers. comm. Kirby).

3 Produced water and deck drainage comingled.

TABLE 2-9

NORTH SEA PRODUCED WATER COMPOSITION

PARAMETER	UNITS	REF. 1	REF. 2	REF. 3	REF. 4	
					$\bar{X}$	Range
Physical Properties						
- temperature	°C	60			-	5 - 60
Major Constituents						
- Total dissolved solids	mg/L	-	-		-	36,000 - 130,000
- Suspended solids	mg/L	-	-		0.2	
- Chloride	mg/L	-	49,550			
- Sulphate	mg/L	377^3	0			
- Calcium	mg/L		2,665			
- Sodium	mg/L		32,930			
- Potassium	mg/L		377			
- Strontium	mg/L	269	550			
- Iron	mg/L	1.5	3.3			
- Magnesium	mg/L		447			
- Bicarbonate	mg/L		425			
- Sulphide	mg/L		0			
- Hydroxyl	mg/L		0			
- Carbonate	mg/L		0			
- Barium	mg/L		218			
Organics						
- TOC	mg/L	199^2				
- Oil (IR)	mg/L	22		$15\text{-}20^1$		-
- high volatiles		153				
- volatiles		25				
- residual organics		25				

REFERENCES:

1 pers. comm. C.S. Johnston
2 Goodman and Troake 1982
3 pers. comm. Davies
4 E & P Forum 1982a

NOTES:

1 Actual concentration considered to be higher because IR method underestimates dissolved aromatics
2 Result from one study. Other North Sea studies have shown TOC to range from 20-800 mg/L.
3 Represents breakthrough of injection water. More typical value is 0.

TABLE 2-10

ANALYTICAL METHODS FOR PRODUCED WATER

REFERENCE	CONSTITUENT	METHOD
Radian Corporation 1982	organic species	GC-IDMS
	extractable organics	fused silica capillary GCMS
	metals	AAS all samples determined in duplicate, and blanks and standards prepared in brine (10 percent NaCl)
Jackson *et al*. 1981	Oil and Grease	Infrared (EPA Storet 00560) Gravimetric (EPA, 1979)
	Ionic analyses of sodium, potassium	Flame emission (API)
	Iron, calcium, magnesium, barium	Atomic absorption (EPA) (API)
	Chloride, sulphate	Autoanalyser (APHA)
	Total dissolved solids	Gravimetric (EPA)
Lysyj 1982 - Produced Water	Trace organics (priority pollutants)	EPA (40CFR136(4))
	metals (priority pollutants)	EPA (40CFR136(4))
	TOL (TOC)	Volatile organics + dissolved nonvolatile organics + suspended organic matter
	Volatile fraction	Principally benzene, toluene, xylene + ethylbenzene, GC - hydrogen flame (CS_2 dissolution)
	Dissolved nonvolatile	0.45 µm HA filter + TOC Standard Method 510 (G)
	Suspended organic	TOC Standard method 510 (G)

Algicides and bactericides were detected in only one produced water sample, that being pentachlorophenol bactericide at a concentration of approximately 0.010 mg/L. Aromatic hydrocarbons were present, but were usually limited to those shown in Table 2-6.

The effect of field age on contaminant concentration in produced water has not been studied thoroughly. One recent study indicated no increase in zinc and benzene concentrations in produced water discharges with age of platform or with percent produced water of the total fluid production (water cut) which generally increases with age of the producing field (Mors et al. 1982).

Total organic carbon values are high for most produced waters, in some cases exceeding 600 mg/L. All the known hydrocarbon constituents in produced water contribute only 50-100 mg/L of this total. Chemical additives for treatment provide perhaps another 50 mg/L carbon (pers. comm. Williams). Analyses conducted to date have not identified the major constituents contributing to these high TOC values although there is some evidence that organic acids may be important (Oldham 1982).

There is considerable dispute over metal values reported for produced water before 1982, because of serious analytical problems. Few heavy metals have been detected in produced water at appreciable concentrations. Notwithstanding the likelihood of analytical errors, zinc appears to occur consistently, and chromium, cadmium and lead are reported in a number of studies conducted. Two recent surveys (Radian Corp. 1982 and Lysyj 1982) have analysed produced water samples for the full range of heavy metals included in the U.S. EPA list of 129 priority pollutants. Only those shown in Table 2-6 for these two references were detected.

1.5 Analytical Methods and Comparisons

Oil and grease measurement techniques for produced water effluents (and all treated oily water discharges) vary from region to region. The U.S. EPA requires the standard gravimetric oil and grease analysis (GR-oil) to be used for monitoring platform discharges in the Gulf of Mexico, coastal California and the Gulf of Alaska. The U.K. government requires that North Sea operators use infrared analysis (IR-oil) for monitoring platform discharges.

The infrared method is appropriate for measuring oil concentrations in produced water on-site, whereas gravimetric analysis must be conducted on shore. The two methods give different results, although the two sets of results often correlate for a given platform or discharge source, (see Figure 2-2 (a-e) from Jackson

FIGURE 2.2 a,b.
INFRARED - GRAVIMETRIC REGRESSION FOR FLOTATION UNIT EFFLUENT

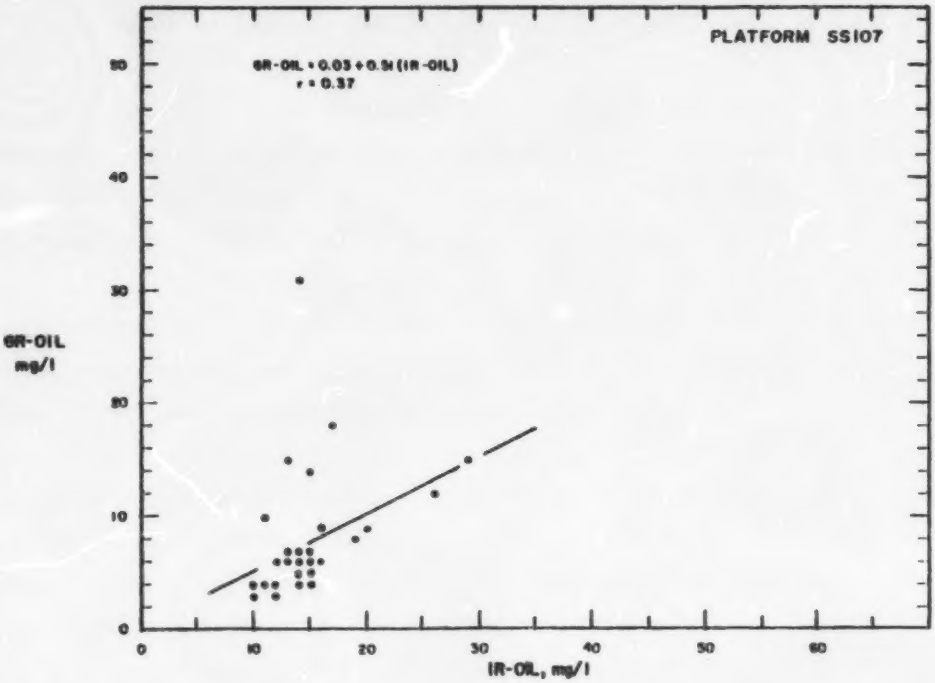

Figure 2-5a Infrared-gravimetric regression, SS107 flotation unit effluent

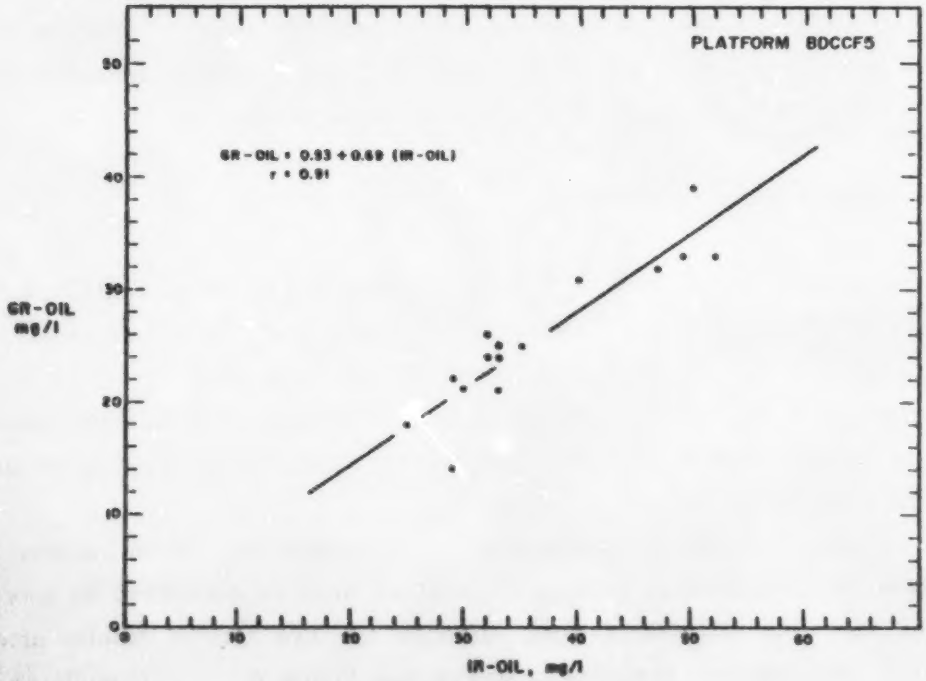

Figure 2-5b Infrared-gravimetric regression, BDCCF5 flotation unit effluent

(SOURCE: JACKSON ET AL. 1981)

FIGURE 2.2 c,d.
INFRARED - GRAVIMETRIC REGRESSION FOR FLOTATION UNIT EFFLUENT

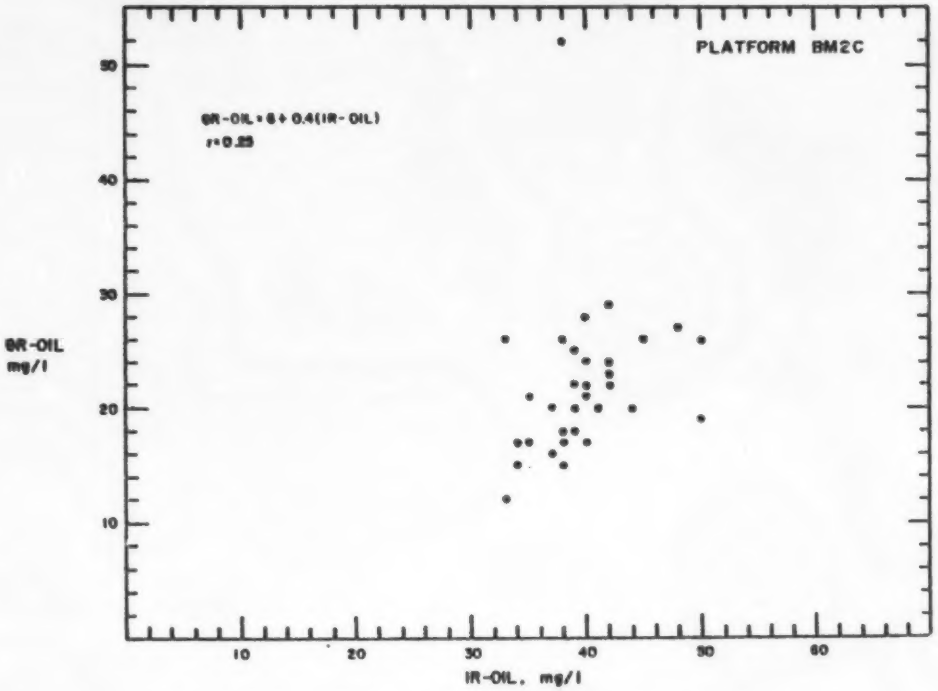

Figure 2-5c Infrared-gravimetric regression, BM2C flotation unit effluent

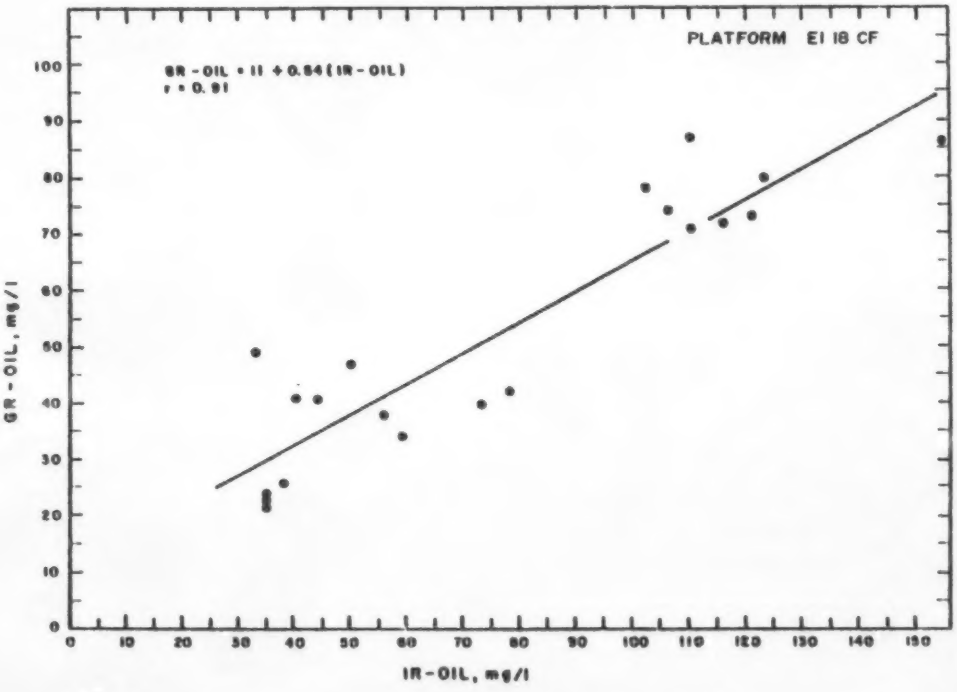

Figure 2-5d Infrared-gravimetric regression, EI18CF flotation unit effluent

(SOURCE: JACKSON ET AL. 1981)

FIGURE 2.2 e.
INFRARED - GRAVIMETRIC REGRESSION FOR FLOTATION UNIT EFFLUENT

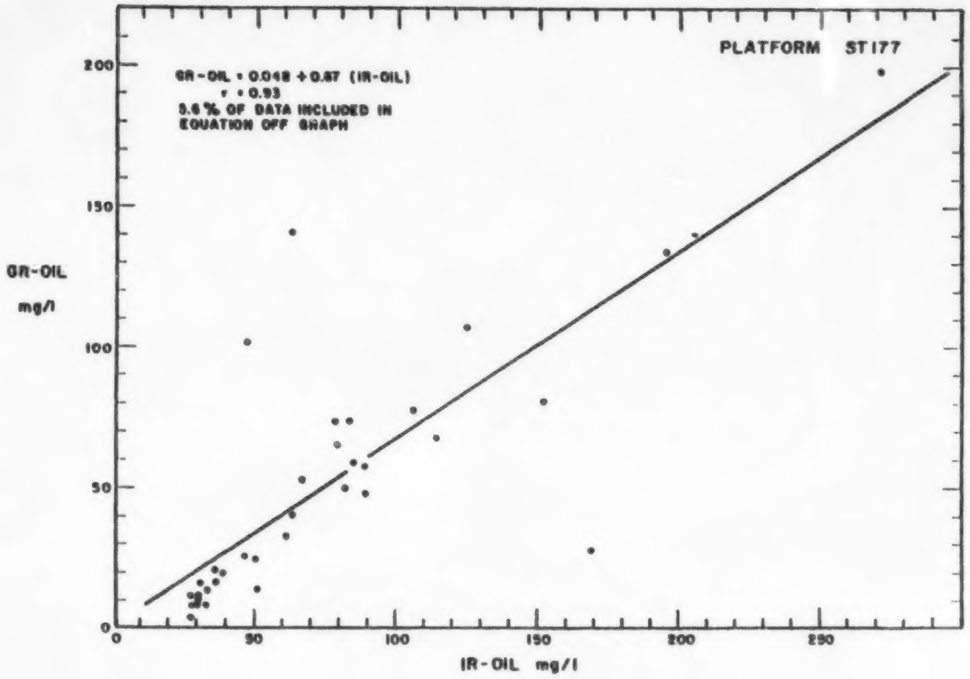

Figure 2-5e Infrared-gravimetric regression, ST177 flotation unit effluent

(SOURCE: JACKSON ET AL. 1981)

et al. 1981). The correlation varies considerably from platform to platform and in some cases no correlation can be drawn. However, the infrared value exceeds the gravimetric value for all platforms sampled in this study. One reason for this is that the infrared method detects light hydrocarbons which may evaporate during gravimetric analysis (pers. comm. Williams).

Infrared methods are considered to underestimate the presence of total oil (hydrocarbon) in North Sea produced water analyses, because a considerable portion of the hydrocarbon in produced water is in the form of aromatics for which infrared detectors have a poor sensitivity (pers. comm. Wilkinson, Davis). Infrared methods depend on calibration curves which apply to a small number of infrared absorbtion wavelengths; consequently compositional differences in the sample being analysed may lead to over-or-underestimations of the amount present. Gravimetric methods, on the other hand, tend to overestimate total oil because they may include substances that are not hydrocarbons (for example, particulates).

Heavy metal analyses of produced water are difficult to perform due to low levels and various sources of interference, such as high salt content (pers. comm. Caudle). No published results are available for heavy metals in North Sea produced waters. Numerous results have been published for produced waters of the three U.S. offshore production areas but some of these have been disputed. The lack of confidence in these metal results has led the U.S. EPA and the U.S. oil industry to develop a protocol for heavy metals and organic priority pollutants in produced water. These methods are outlined in Radian Corp. (1982).

2.0 Drilling Fluids and Cuttings

2.1 Introduction

Drilling fluid is a suspended solution of solids and dissolved materials in a carrier liquid, either fresh water, sea water or oil. Drilling mud is the combination of materials mixed on the surface before circulation through the drill hole, whereas drilling fluid is this mixture once it has circulated through the well to the platform (Mors et al. 1982). Drill cuttings comprise the formation cuttings which are circulated through the well to the platform surface, together with drilling fluid which adheres to the formation cuttings.

Drilling fluids are classified by: (1) the liquid phase used to carry all other constituents; (2) the major constituents added to control the mud properties; and (3) their density or mud weight (Petrazzuolo 1981). Major fluid types are:

(i) freshwater - base mud
sea water - base mud
oil - base mud

(ii) polymer - gel mud
lignosulphonate mud
potassium chloride mud

(iii) low - weight (density) mud
mid - weight (density) mud
high - weight (density) mud

Drilling fluids vary in composition and characteristics from region to region, well to well and over depth for a particular well. Consequently, specific or custom drilling muds are formulated for each drilling operation, to account for the specific formation conditions downhole. Major factors which influence fluid composition are (Petrazzuolo 1981):

- initial mud type
- volume and type of additives
- need for new mud system at different depths
- geochemical composition of the drilled formation
- formation temperature
- formation pressure

Although the total volume of drilling fluids and cuttings discharged from an offshore area is much greater for development wells than for exploratory wells (because of the closer spacing and larger number of wells drilled from one platform) most available data apply to exploration wells(1). Much of the data presented in this section, therefore, are based on exploration well experience. Basic mud composition and discharge volumes do not change greatly between exploration and development wells for a given location, with some exceptions: oil-base muds may be used for a portion of a development well, but seldom for exploration wells; and, development wells are usually shallower (because the hydrocarbon-bearing zone is known) allowing lower density muds to be used (pers. comm. Sauer).

2.2 Discharge Rates

Water-base drilling fluids and cuttings are usually discharged to the sea, following solids control treatment which allows a portion of the drilling fluid to be recycled. In some cases, the final drilling fluid at the completion of a well may be saved and either taken to another offshore well for re-use, or taken to shore for future use. In most cases, however, it is discharged overboard.

Drilling fluid and cuttings discharges can be continuous or bulk. Continuous discharges of cuttings and of fluids come from the solids control equipment. Bulk discharges (commonly known as active mud discharges or mud tank dumps) are discharges of whole drilling fluids and cuttings. Bulk discharges involve large volumes of fluids and cuttings (16 to 190 m^3), at high rates of discharge (80 to 110 m^3/h) and last only for a period of 20 minutes to 3 hours (Mors _et_ _al_. 1982; Petrazzuolo 1981). Bulk discharges can occur from a few (bulk volume) to 20 to 30 times (small volume) over the life of a well. Such discharges usually are required when:

(i) drilling fluid is removed to allow water dilution;

(ii) a change in drilling fluid type is required (one to three times over the life of a typical well);

or (iii) mud tanks are emptied at the end of a well (Petrazzuolo 1981).

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(1) Development wells are drilled into known formations to allow production of oil and gas from the reservoir

The largest bulk discharges occur early in drilling when casing is placed at mid well where mud type may be changed, and at completion of the well when mud tanks are emptied (Petrazzuolo 1981).

Continuous discharges are continuous in the sense that, while drilling occurs, they are required. In practice, drilling and the attendant fluid and cuttings discharges may occur between 30 and 50 percent of the time a rig is on location (Petrazzuolo 1981; Mors et al. 1982).

Drilling fluid chemicals are usually recorded on a "use" or "material added" basis for each fluid constituent. Only discharges of whole mud are recorded. The percentage of mud chemicals added to the system which are discharged to the sea varies from approximately 25 to 90 percent (Petrazzuolo 1981). One estimate for the Beaufort Sea ranged from 52 to 78 percent of mud additives actually discharged (Hrudey 1979).

Tables 2-11 and 2-12 show continuous and bulk discharge data from a number of U.S. exploratory wells. A development well is typically drilled to a lesser depth than an exploration well, has similar diameter at a given depth, and is longer for a given depth because it is drilled at an angle (deviated well). For a given reservoir depth,therefore, mud and cuttings volumes are greater for a development well. Estimates of discharge rates and volumes for Canadian development wells are given in Chapter 7, Table 7-5.

2.3 Composition and Usage

2.3.1 Water-Base Drilling Muds

Drilling muds are composed of a small number of major constituents which account for over 90 percent of the total weight of drilling products used in the U.S., and a combination of any of a large number of chemical additives which account for the remaining 10 percent of mud products (Mors et al. 1982). The major constituents are barite, bentonite or other clay, lignosulphonates, lignite, caustic soda and sodium carbonate/bicarbonate. Table 2-13 lists the major constituents and other groups of chemical additives commonly used in drilling of wells, in approximate order of usage, and the principal function of each.

TABLE 2-11

SUMMARY OF CONTINUOUS DRILLING WASTE DISCHARGES

Source: Petrazzuolo 1981

LOCATION	TOTAL DISCHARGE		DRILLING FLUIDS		DRILL CUTTINGS	
	m^3/day	bbl/day	m^3/day	bbl/day	m^3/day	bbl/day
Lower Cook Inlet	19-40	120-250	15-33	93-203	4-8	27-47
Gulf of Mexico	26	163	19	116	8	47
mid-Atlantic	30	188	25	155	5	33
mid-Atlantic	36-41	225-254	30-35	19-219	6	35
S. California OCS (not included in average)	5-8	33-50	5-8	33-50	1-3	7-22
Average	30	190	24	150	6	40
Range	19-41	120-255	14-35	90-220	5-8	30-50

TABLE 2-12

SUMMARY OF BULK DRILLLING WASTE DISCHARGES

Source: Petrazzuolo 1981

LOCATION	RATE		DUMP VOLUME		MAXIMUM POSSIBLE DAILY DISCHARGE					
					Fluids		Cuttings		Total	
	m^3/h	bbl/hr	m^3	bbl	m^3	bbl	m^3	bbl	m^3/d	bbl
Lower Cook Inlet	96-112	600-700	32-336	200-2,100	-	-	-	-	339-360	2,120-2,250
Gulf of Mexico	5-19	30-120	128-160	800-1,000	560	3,500	46	290	-	-
mid-Atlantic	-	-	96-160	600-1,000	248	1,550	74	465	-	-
mid-Atlantic	-	-	48-320	300-2,000	320	2,000	272	1,700	-	-
Gulf of Mexico (typical)	40	250	-	-	-	-	-	-	-	-

TABLE 2-13

COMMON DRILLING MUD CHEMICAL ADDITIVES

FUNCTION	COMPOUNDS
Weighting Materials	Products with high specific gravities, predominantly barite, calcite, ferrophosphate ores, siderite, and iron oxides (hematite), are used to increase drilling mud weight.
Gelling Agents	Bentonite clay most common; attapulgite or sepiolite clays for high formation brine concentration.
Thinners and Dispersants	Lignosulfonates, tannins, lignite and various polyphosphates such as sodium acid pyrophosphate (SAAP); act by deflocculating associated clay particles.
Alkalinity and pH Control Agents	Caustic soda, sodium carbonate, sodium bicarbonate,and lime commonly used to control the alkalinity of the drilling fluid and secondarily to control bacterial growth.
Pipe Release Agents	Surfactants and detergents in mineral oil, straight diesel oil systems for specialized purposes such as freeing a stuck pipe.
Filtrate Loss Reducers and Viscosifiers	Bentonite clays, a range of cellulose polymers such as sodium carboxymethyl cellulose (CMC) and hydroxyethyl cellulose (HEC), and pre-gelled starch, xanthum and guar gum polymers, added to drilling fluid to prevent loss of the liquid phase into the formation.
Lost Circulation Materials	Wood chips or fibres, mica, sawdust, leather, nut shells, cellophane, shredded rubber, fibrous mineral wool, and perlite all used to plug pores in the well-bore wall and to reduce or stop fluid loss into the formation.
Shale Control Inhibitors	Gypsum, sodium silicate, polymers, limes, potassium chloride and salt reduce wall collapse caused by swelling or hydrous distintegration of shales.
Flocculants	Salt (or brine), hydrated lime, gypsum, and sodium tetraphosphate cause suspended colloids to flocculate.
Scale Inhibitors	Caustic soda, soda ash, sodium bicarbonate, and certain polyphosphates added to control the calcium buildup which prevents proper functioning of drilling equipment.

TABLE 2-13 (continued)

COMMON DRILLING AND CHEMICAL ADDITIVES

FUNCTION	COMPOUNDS
Surface Active Agents (Surfactants)	Emulsifiers, demulsifiers, and flocculants reduce the relationship between viscosity and solids concentration, vary the gel strength, and reduce the fluid plastic viscosity.
Foaming Agents	Surfactants and detergents, such as ethoxylated alkyl phenols and organic sulphonates, designed to foam in the presence of water and allow air or gas release when drilling through formations producing water.
Defoamers	Aluminum stearate, sodium aryl sulfonate, tributyl phosphate, alcohols designed to reduce foaming action, particularly in brackish waters and saturated saltwater muds.
Emulsifiers	Ethyl hexanol, silicone compounds, modified lignosulfonates, and anionic and non-ionic products are used as emulsifiers to create an homogeneous mixture of two liquids.
Corrosion Inhibitors	Hydrated lime and amine salts added to drilling fluids to reduce corrosion.
Lubricants	Certain hydrocarbons, mineral and vegetable oils, graphite powder, and soaps used as lubricants to reduce friction between the drill bit and the formation.
Biocides	Paraformaldehyde, gluteraldehyde, dithiocarbamates, alkylamines, quaternary amines, caustic soda, lime, and starch preservatives typically used to reduce the bacteria count in the mud system. Halogenated phenols are no longer permitted for offshore use in the U.S.
Oxygen Scavenger	Sodium, ammonium bisulphite
H_2S Scavenger	Sodium dichromate; zinc carbonate, sulfonate, chromate
Drill Pipe/Collar Dope	Copper, lead, zinc.
Permafrost well-bore Temperature Depressant	Potassium chloride; relatively high use in Canadian Arctic.

Source: Adapted from Mors et al. 1982
API 1978
Neff 1982
Read and Whitehead 1981

With an increasing emphasis on the screening of drilling fluid products to remove the more toxic formulations and compounds used in the past, the U.S. EPA and the oil industry in the U.S. have co-operated in developing a number of standard or "generic" mud formulations which are representative of different muds used for a number of offshore situations, and are considered to have an acceptably low level of toxicity. Table 2-14, which lists these generic muds, provides a good cross-section of mud types commonly used in offshore environments. The spud mud and seawater mud formulations are used in the upper portions of a well, while freshwater formulations are used for the deeper sections. Specialty chemicals, which are added on a case-by-case basis, are not listed in these formulations.

There is a change in mud characteristics with mud weight (density). The light-weight muds which are used in the upper portions of a well (0-3000 m) have low solids content and a relatively low density. The high- weight muds which are used in the lower portions of a well (3,000-6,000 m) have a higher solids content and a high density due to a high proportion of barite in the formulation. The relative properties of different weight muds are shown in Chapter 7, Table 7-5.

Chemical usage generally increases with well depth; barite dominates the total drilling muds and drilling fluid discharges in the deeper wells. The nature of the additives also changes, with near-surface mud consisting mostly of caustic soda and bentonite. Deeper-well muds contain increasing amounts of barite, lignosulfonate and lignin (Neff 1982). Figures 2-3 to 2-5 are plots of usage with mud depth for five major mud additives.

In the Canadian Arctic, potassium chloride (KCl or potash) mud formulations are used to drill through permafrost which may extend to over 600 m depth, because KCl acts as a freezing point depressant (Friesen 1980). Below this depth, use of KCl is reduced. KCl muds have also been used for drilling through sensitive formations such as swelling or sloughing shales. Canadian and U.S. companies are considering use of KCl mud systems for development drilling in the place of oil-base muds. Concentrations of KCl used in Canadian Arctic surface wells range from 29 to 58 kg/m^3 (Neff 1982 citing Bryant 1976). The use of KCl in whole mud ranges from 15 to 140 kg/m^3 when used in sensitive deeper formations instead of in permafrost drilling.

Metals in drilling fluids can be divided into two categories: those which are normal components of clays and salts used in mud formulations (calcium, magnesium, aluminum and sodium) and which are not considered to be of environmental concern; and, heavy metals which are associated with a small number of major mud components (principally with barite and lignosulfonates) (Neff 1982). The heavy metal content of whole muds is highly variable because of large differences in the

TABLE 2-14

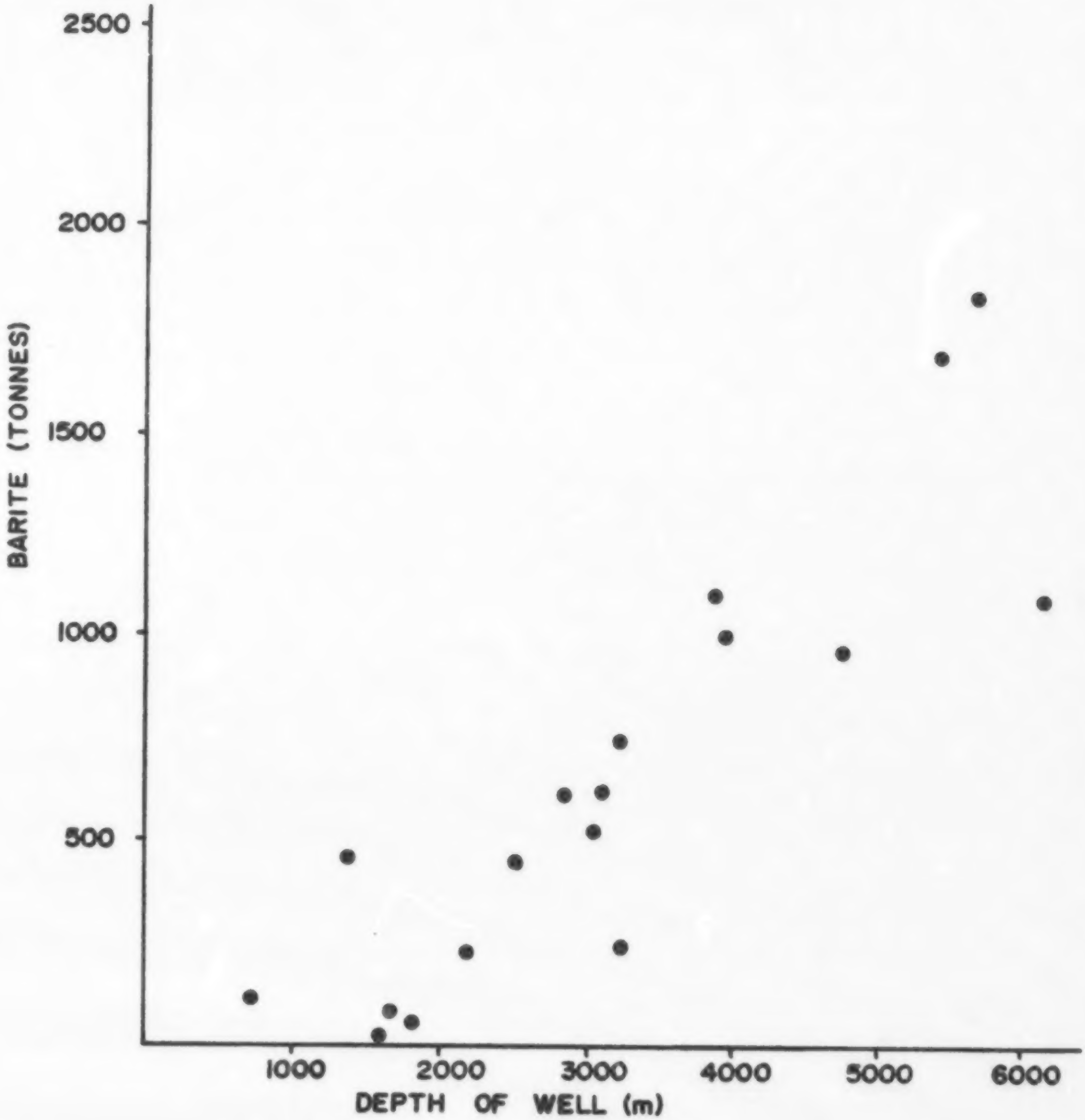
COMMON DRILLING FLUID TYPES - UNITED STATES OFFSHORE

DRILLING FLUID TYPE	MAJOR COMPONENTS	USE RATE IN WHOLE MUD (kg/m^3)	USE RATE IN WHOLE MUD (lb/bbl)
Spud Mud	Attapulgite/bentonite	30 - 140	10 - 50
	Barite	0 - 140	0 - 50
	Lime	1 - 2	0.5 - 1.0
	Caustic (NaOH)	0 - 6	0 - 2
	Soda ash/sodium bicarbonate	0 - 6	0 - 2
	Sea water	as needed	
Saltwater/KCl/ Polymer Mud	Barite	0 - 1,280	0 - 450
	Drilled solids	60 - 280	20 - 100
	KCl	15 - 140	5 - 50
	Starch	6 - 35	2 - 12
	Cellulose polymer	0.7 - 15	0.25 - 5
	Caustic (NaOH)	1 - 9	0.5 - 3
	Xanthum gum polymer	0.7 - 6	0.25 - 2
	Sea water	as needed	
Seawater Gel Mud	Drilled solids	60 - 280	20 - 100
	Barite	0 - 140	0 - 50
	Attapulgite/Bentonite	30 - 140	10 - 50
	Caustic (NaOH)	1 - 9	0.5 - 3
	Cellulose polymer	0 - 6	0 - 2
	Lime	0 - 6	0 - 2
	Soda ash/sodium bicarbonate	0 - 6	0 - 2
	Sea water	as needed	
Seawater Lignofonate Mud	Barite	70 - 1,280	25 - 450
	Drilled solids	60 - 280	20 - 100
	Attapulgite/Bentonite	30 - 140	10 - 50
	Lignosulfonate	6 - 40	2 - 15
	Lignite	3 - 30	1 - 10
	Caustic (NaOH)	3 - 15	1 - 5
	Cellulose polymer	0.7 - 15	0.25 - 5
	Soda ash/sodium bicarbonate	0 - 6	0 - 2
	Sea water	as needed	
Lightly Treated Lignosulfonate Freshwater/ Seawater Mud	Barite	0 - 500	0 - 180
	Drilled solids	60 - 280	20 - 100
	Bentonite	30 - 140	10 - 50
	Lignosulfonate	3 - 17	2 - 6
	Lignite	0 - 11	0 - 4
	Caustic (NaOH)	3 - 9	1 - 3
	Cellulose polymer	0 - 5	0 - 2
	Lime	0 - 6	0 - 2
	Soda ash/sodium bicarbonate	0 - 6	0 - 2
	Sea water	as needed	
Lignosulfonate Freshwater Mud	Barite	0 - 1,280	0 - 450
	Drilled solids	60 - 280	20 - 100
	Bentonite	30 - 140	10 - 50
	Lignosulfonate	11 - 42	4 - 15
	Lignite	6 - 30	2 - 10
	Caustic (NaOH)	6 - 15	2 - 5
	Cellulose polymer	0 - 6	0 - 2
	Lime	0 - 6	0 - 2
	Soda ash/sodium bicarbonate	0 - 6	0 - 2
	Defoamer/detergents	0	0
	Freshwater	as needed	
Lime Mud	Barite	70 - 500	25 - 180
	Drilled solids	60 - 280	20 - 100
	Bentonite	30 - 140	10 - 50
	Lime	6 - 60	2 - 20
	Lignosulfonate	6 - 40	2 - 15
	Lignite	0 - 30	0 - 10
	Caustic (NaOH)	3 - 15	1 - 5
	Soda ash/sodium bicarbonate	0 - 6	0 - 2
	Freshwater	as needed	
Nondispersed Mud	Barite	70 - 500	25 - 180
	Drilled solids	60 - 200	20 - 70
	Bentonite	15 - 40	5 - 15
	Acrylic program*	1 - 6	0.5 - 2
	Freshwater	as needed	

Source: Petrazzuolo 1981

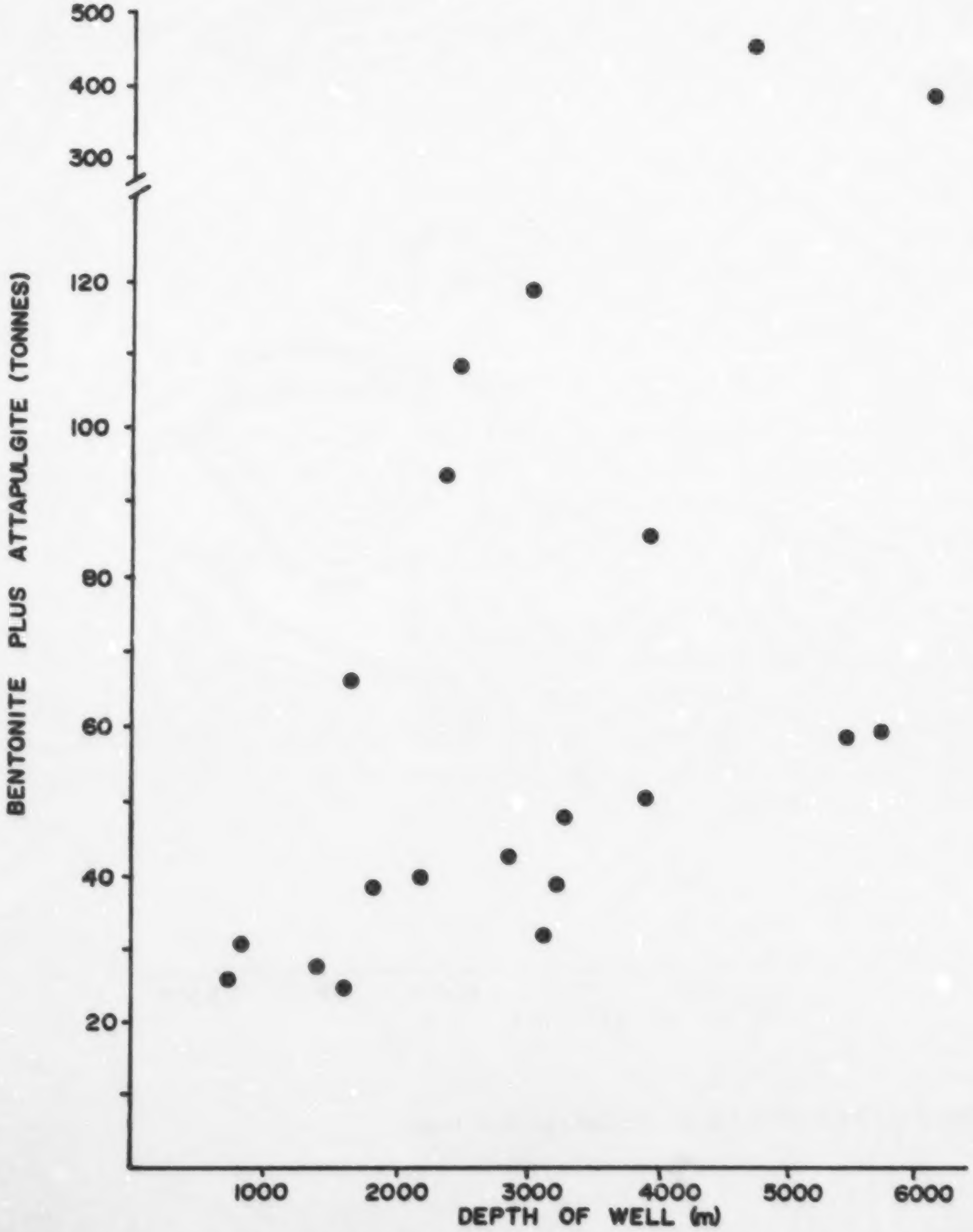
* polyacrylates and polyacrylamides

FIGURE 2·3
BARITE USE VERSUS WELL DEPTH



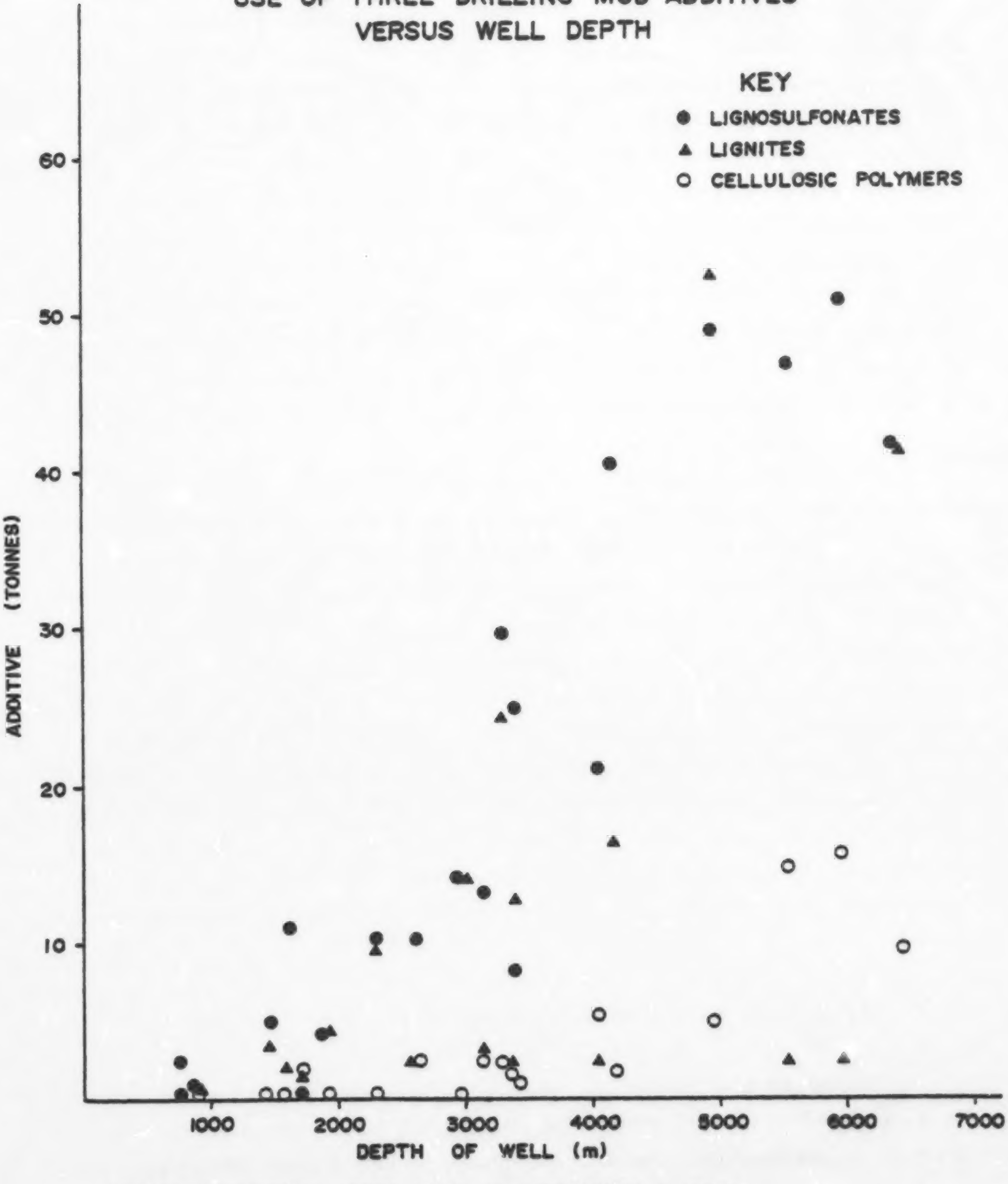
(SOURCE: ADAPTED FROM PETRAZZUOLO 1981)

FIGURE 2-4
BENTONITE PLUS ATTAPULGITE CLAYS USE VERSUS WELL DEPTH



(SOURCE: ADAPTED FROM PETRAZZUOLO 1981)

FIGURE 2·5
USE OF THREE DRILLING MUD ADDITIVES VERSUS WELL DEPTH



(SOURCE: PLOTTED FROM DATA IN PETRAZZUOLO 1981) formulations of different muds and because of impurities which may be associated with some of the mud products. Barite often contains low concentrations of various metal impurities including lead, zinc, mercury, arsenic, chromium and cadmium. The solubilities in seawater of these contaminants, however, are low (Mors et al. 1982). Chrome lignosulfonates contain relatively high concentrations of chromium compared to ferrochrome lignosulfonates. Other sources of chromium in drilling fluids are corrosion inhibitors and cross-linking agents for X-C polymers (xanthum gums) (Osborne 1982). Chromium in lignosulfonate compounds is in the trivalent oxidation state, whereas it is in the hexavalent state in the salt additives (such as corrosion inhibitors), before it is mixed into the mud. The hexavalent chromium is reduced to the more stable trivalent state by organic compounds and high temperatures in the mud. Most of the chromium discharged as waste drilling fluid or attached to cuttings therefore will be Cr^{3+} (Moseley 1980). Tables 2-15 and 2-16, taken from Neff (1982), show trace metal concentrations which have been found in specific mud components and in whole muds of various types.

The major sources of heavy metals in drilling fluids are barite and lignosulfonate compounds, although high levels of one or two heavy metals have been found, on occasion, to result from additives with a low use rate, but high metal concentration. For instance, drill collar and pipe dope are used in only very small amounts in the drilling of a well, compared to other constituents, but their high zinc, lead and copper contents have been cited as major contributors to these heavy metals found in drilling fluid discharges (Ayers et al. 1980). Zinc salts used as H_2S scavengers in drilling fluids are another potential source of zinc contamination.

Water-base drilling fluids sometimes become contaminated with oil. Diesel oil is added to the drilling mud to free a stuck drill pipe. From 0.5 to 5 percent (by volume) diesel may be added to the mud mixture, with 0.5 to 1 percent being a typical range. This mud is usually segregated when it comes to surface, but may occasionally pass into the solids control system and be discharged (pers. comm. Sauer).

2.3.2 Cuttings from Water-Base Mud Systems

Discharged drill cuttings are composed of: (1) formation cuttings which have been circulated through the well to the platform; (2) wash water which is used to separate drilling fluid from the cuttings; and, (3) residual drilling fluid which is not removed from the cuttings (Ray and Meek 1980). Before discharge of cuttings

TABLE 2-15

TRACE METAL CONCENTRATIONS IN DRILLING FLUID COMPONENTS
(mg/kg dry weight)

Material	Ba	Cr	Cd	Cu	Fe	Hg	Pb	Zn	Others		Reference
Barite (vein deposits)	NA	NA	0.6-32	0.6-560	200-59,000	0.8-28	<2-3,370	<0.2-3,020	0.008-170 15-41	As Ni	Kramer et al. 1980
Barite (bedded deposits)	NA	NA	0.5-0.7	5.4-7.6	2,500-6,000	0.13-0.26	1-1.8	6-10	1.4-1.8 0.5-5.7	As Ni	Kramer et al. 1980
Barite	NA	54	NA	44	34,900	NA	286	1,270	-		Beak Cons. 1974
Barite	55,000	3.6	NA	NA	NA	0.054	< 1.0	NA	-		ECOMAR 1978
Barite	NA	0-3	NA	4-30	30-1,500	NA	0	NA	-		Perricone 1980
Barite	NA	< 10	<2	NA	NA	<1	< 10	< 5	-		Ayers et al. 1980
Barite	NA	2.5	10.0	NA	NA	14.2	890	2,100	25.7	As	Crippen et al. 1980
Barite	501,000	NA	NA	91	21,700	NA	1,370	2,750	-		Trefry et al. 1981
Barite	NA	11	NA	290	9,500	NA	19	19	-		Trefry et al. 1981
Barite (Mineral King)	-	-	-	0.300	-	0.011	2.00	3.50	-		MacDonald 1982
Barite (Vein replacement)	-	-	6.9	126	-	10.5	523	1,845	128	As	Soniassy 1982
Barite (Bedded)	-	-	6.6	6.6	-	0.19	1.4	7.9	1.6	As	Soniassy 1982
Barite (Mountain Minerals pure)	-	-	2.0	2.0	-	0.65	14	55	0.2	As	Soniassy 1982
Bentonite Clay	560	3.3	NA	NA	NA	NA	NA	NA	-		ECOMAR 1978
Bentonite Clay	NA	< 10	<2	NA	NA	<1	< 10	57	-		Ayers et al. 1980
Bentonite Clay	NA	1.5	0.6	NA	NA	0.02	22.5	31.5	0.7	As	Crippen et al. 1980
Chrome Lignosulfonate	64	24,300	-	-			< 1.0		-		ECOMAR 1978
Chrome Lignosulfonate	NA	925	1.4	NA	NA	0.02	2.5	5.9	0.25	As	Crippen et al. 1980
Chrome Lignosulfonate	NA	39,100	NA	8	1,250	NA	10	17	1,440	Mn	Trefry et al. 1981
Chrome Lignosulfonate/Lignite Is	NA	14,600	<2	NA	NA	<1	< 10	15	-		Ayers et al. 1980
Ferrochrome Lignosulfonate (Peltex)	NA	16,100	NA	11	36,700	NA	< 0.25	1.2	-		Beak Cons. 1974
Iron Lignosulfonate (DFE 506)	NA	53	NA	3.3	74,300	NA	< 0.25	1.8	-		Beak Cons. 1974
Lignite	NA	300	5.5	NA	NA	NA	< 1.0	NA	-		ECOMAR 1978

Source: Adapted from Neff 1982

All references as in Neff 1982, except: MacDonald 1982; Soniassy 1982.

NA - not analysed.

TABLE 2-16

TRACE METAL CONCENTRATIONS IN DRILLING MUDS FROM VARIOUS SOURCES
(mg/kg dry weight)

Drilling Mud	Ba	Cr	Cd	Cu	Fe	Hg	Pb	Zn	Others	Reference
11 Samples Canadian Beaufort (Issungnak Exploration Well)		1-26	0.1-6.0	0.8-24		0.1-0.7		27-614		pers. comm. Psutka
48 Samples Canadian Arctic Muds	NA[5]	0.1-999	NA	<0.05-250	0.002-9,250	NA	NA	0.06-1,700		Siferd 1976
3 Barite CLS[1] Muds	NA	NA	0.16-54.4	6.4-307	NA	0.2-10.6	0.4-4,226	6.6-12,270	3.8-19.9 Ni	Nelson et al. 1980
2 Mid-Atlantic CLS Muds	229,100-303,700	1,112-1,159	0.6-0.8	5.8-7.7	NA	<0.05	102.6-218.5	36.0-48.4	1.8-2.3 As 13.5-17.0 Ni 22.7-28.0 V	Ayers et al. 1980
3 Mid-Atlantic CLS Muds	823-19,300	57-90	<2	NA	NA	<1-2.8	<10-241	101-197	20-33 Ni 14-20 V	EG & G 1980
Baltimore Canyon CLS Mud	202,000	850	NA	20	19,000	NA	NA	NA		Liss et al. 1980
Gulf of Mexico CLS Mud	133,000	200	NA	280	16,000	NA	NA	NA		Liss et al. 1980
Gulf of Mexico Spud Mud[2]	NA	51	0.51	NA	NA	NA	NA	NA		Page et al. 1980
Gulf of Mexico High Density CLS Mud[2]	NA	257	0.78	NA	NA	NA	1.3	NA		Page et al. 1980
Gulf of Mexico Mid-Density CLS Mud[2]	NA	396	1.70	NA	NA	NA	5.0	NA		Page et al. 1980
mid-Atlantic Low-Density CLS Mud	NA	596	1.18	NA	NA	NA	NA	NA		Page et al. 1980
Gulf of Mexico Seawater CLS Mud	NA	485.2	3.0	48.2	NA	NA	179.4	251.4		McCulloch et al. 1980
Gulf of Mexico Spud Mud[2]	NA	10.9	3.5	30.2	NA	NA	134.2	297.3		McCulloch et al. 1980
Gulf of Mexico High Density CLS Mud	NA	229.9	10.9	118.8	NA	NA	209.5	274.5		McCulloch et al. 1980
Gulf of Mexico Mid-Density CLS Mud[2]	NA	416.7	19.2	127.0	NA	NA	915.3	604.8		McCulloch et al. 1980
2 CMC[3]/Gel Muds Alaska[4]	4,400-6,240	28-63	<0.5-0.6	6.4-10.4	NA	0.017-0.031	2.4-12.8	42-64		Tornberg et al. 1980
XC Polymer Muds Alaska[4]	720-1,120	66-175	<0.5-1.5	10-16	NA	0.015-0.070	5.6-56	49-110		Tornberg et al. 1980
XC Polymer/Unical Muds Alaska[4]	NA	56-125	NA	2.8-17.0	NA	0.028-0.217	9-117	198-397		Tornberg et al. 1980
CLS Muds Alaska[4]	800-7,660	121-172	<0.5	10-12	NA	0.03-0.07	16.4-56.0	49-56		Tornberg et al. 1980
Gulf of Mexico CLS Mud	90,000	500	NA	43	27,000	NA	91	370	400 Mn	Trefry et al. 1981
Mobile Bay Treated CLS Mud	NA	3,960	NA	47	10,100	NA	22	340	290 Mn	Trefry et al. 1981

1. CLS, chrome lignosulfonate
2. The same muds were analyzed by Page et al. 1980 and McCulloch et al. 1980
3. CMC, carboxymethylcellulose
4. Concentrations given on a wet weight basis
5. NA, not analyzed.

Source: Neff 1982. All references are as shown in Neff 1982.

overboard, the drill cuttings and fluid mixture which has returned from the well are passed through a series of separator devices, known as solids control equipment, which removes the larger cuttings particles from the system and allows the fluid to be recirculated. The final cuttings discharge comprises coarse particles (rock chips), sand and clay particles.

Drill cuttings are seldom analysed for environmental monitoring purposes, although geologists evaluate cuttings to assess the properties of the formations being drilled. The chemical composition of the cuttings is primarily that of various formation rock materials such as quartz, natural clays and others, depending on the formation being drilled. A typical density for a cuttings discharge is 1.7 g/cm^3 and solids content (including wash water) is 65 percent (wt/wt) (Ayers 1981). Various heavy metals may be found in drill cuttings. They originate in the formation rock or are associated with drilling fluids adhering to the cuttings. Metal concentrations in discharge from the shale shaker were reported by Ayers (1981) as barium 3,160 mg/kg, chromium 44 mg/kg, cadmium < 2 mg/kg, lead 10 mg/kg, mercury < 1 mg/kg, nickel 15 mg/kg, vanadium 11 mg/kg and zinc 80 mg/kg.

Crude oil from the formation fluids may contaminate cuttings brought to the surface while the well passes through the hydrocarbon-bearing zone. In exploration wells an oil content of 0 - 5% of drill cuttings from this zone has been measured by (pers comm. Swiss). In the North Sea, contamination of cuttings by crude oil from development wells has not been detected, even using high resolution capillary GC-MS analysis (pers. comm., Johnston).

2.3.3 Oil-Base Drilling Muds

Oil-base drilling muds are those in which oil, usually diesel oil, is the carrier for all other mud additives and in which water or brine may be emulsified in the oil (McMordie 1980). Some well conditions such as salt and shale formations, may require the use of oil-base mud systems, to limit formation damage (by preventing sloughing, hydration and swelling of shales and clays), to provide better lubrication, and to remain stable at higher temperature than water-base muds. They are used for the lower portions of deviated development wells (Kelly et al. 1980; McMordie 1980).

Oil-base muds are not discharged to the sea for environmental and cost reasons. Cuttings from oil-base mud system use are discharged following appropriate cleaning to remove oil. The handling of used oil-base muds is described in Chapter 4, Section 1.2.2.

Oil-base muds have only recently been used in offshore U.S. areas. Their use in the future may be limited because restrictions on their use have included hauling oil-contaminated cuttings to shore in some state waters. Use in the Gulf of Mexico, however, is increasing (pers. comm. Sauer). Oil-base mud systems have been used to a considerable extent in both Norwegian and U.K. waters of the North Sea, and are increasing in use.

A typical diesel oil-base mud formulation is shown in Table 2-17. Such muds are characterized by a low-viscosity oil (usually diesel) as the continuous phase, water with a high salt content (typically 250,000 - 400,000 mg/L calcium chloride) in the emulsified water phase, and emulsifiers and stabilizers (Simpson 1979).

Since 1982, interest has grown in the use of "low-toxicity" oil-base mud systems, which use a paraffin oil instead of diesel for the oil phase. The paraffin or mineral oil is a refined oil which has had a portion of its aromatic and naphthenic constituents removed. These mud systems have advantages of lower direct toxicity to aquatic organisms and increased safety to drilling crews (diesel-base muds cause skin irritation and can create fume problems on the platform deck).

Many different oil bases are being used for the low-toxicity oil muds. The most common is "Mentor-28" which is also used in products having household and industrial applications. The aromatic content of this and other mineral oils varies with the refinery where it is produced. Mentor-28 was previously manufactured in the U.K. where it had an aromatic content of 5 to 6 percent. The American-manufactured Mentor-28, which was the basis for most of the low-toxicity drilling mud formulations in use in 1982, has an aromatic content of 15 to 20 percent, mostly in the form of 3-ring aromatics; much of the 1-ring and 2-ring aromatic compounds have been removed (pers. comm. Sauer). Diesel oil, by comparison, contains about 25 to 30 percent aromatics. Assuming that the oil phase of a low-toxicity mud is 30% (by wt.), the aromatic content of the whole mud would be 5-6%. A typical composition for a low-toxicity mud is shown in Table 2-18.

Specialty paraffin oils may have aromatic contents as low as 1 to 4 percent, but have not been used widely in low- toxicity muds. Recent drill tests have been conducted successfully by Conoco in the Gulf of Mexico using a paraffin oil mud system having an aromatic content of 0.1^{o}/o (Boyd et. al. 1983).

TABLE 2-17

TYPICAL OIL-BASE MUD FORMULATION AND PROPERTIES

Properties(1)	
Density	1.5 g/cm^3 (12.5 lb/gal)
Percent oil (vol.)	58
Percent water (vol.)	20
Percent solids (vol.)	22
Oil:Water Ratio	76:24

Composition(2)	Weight Percent	Typical Constituents
Diesel	30	-
Water (sea water)	13	-
Barite	39	Barium sulphate
Calcium chloride	7	-
Oil stabilizer	3.6	Asphaltene
Emulsifier	0.8	Ethoxylated tall oil; resin polyamine
Filtration control agent	3.2	Starch, cellulose
Lime	2.0	-
Clay	1.2	Organophilic (quaternary amine) bentonite

Sources: (1) Cranfield no date
(2) Adapted from Espey, Huston and Associates, Inc. 1982

TABLE 2-18

COMPOSITION OF A TYPICAL PARAFFIN-BASE MUD

		CONCENTRATION
Mud Weight		1.2 g/cm^3 (10 lb/U S gal)
Low-aromatic oil (paraffin)		30% (by volume)
Water		29% (by volume)
Barite		27% (by volume)
Sodium chloride		12% (by volume)
Lime		2% (by volume)
Clay	- (Organophilic clay)	
Emulsifier	- (Fatty acid amide)	
Dispersant and oil wetting agent	- (Modified imidazoline)	
High temperature stabilizer	- (Gilsonite (asphaltene))	3% (by volume)
Dispersant	- (Calcium sulphonate)	
Emulsifier component	- (Calcium oxide)	

Source: Chromalloy 1982.
Note: Rounding error results in total = 103 percent.

2.3.4 Cuttings from Oil-Base Mud Systems

When oil-base mud systems are used, cuttings recovered in the solids control system (shale shaker and attendant size separators) are directed to a cuttings wash system before discharge to reduce the oil content of the cuttings. As described in Chapter 4, Section 1.2.2, oiled cuttings handling practice varies by region and operator. The cuttings washing process may involve the use of water, diesel oil or other solvent, or various degreasers and surfactants. Trace amounts of chemicals used to wash cuttings will adhere to the cuttings when discharged. These chemicals include surfactant materials such as ethoxylated fatty acids and ethoxylated glycols mixed with alcohols, chloride salts and lime (Exxon Company U.S.A. 1982) and n-butyl cellusolve (Read and Whitehead 1981). One estimate of use rate for cleaning chemicals is 200 litre wash solution, 200 litre degreaser and 200 litre oil dispersant per well over a depth interval of 300 m to 3,000 m (Holder 1982b).

Oil remaining with the cuttings following cleaning is in three forms: absorbed into the cuttings particles, adsorbed on the particles, and free oil which has not been removed by cleaning. Results obtained from monitoring and estimates for residual oil associated with discharged cuttings are variable. Table 2-19 is a summary of data for both diesel-base muds and paraffin-base muds. Typical values for residual oil are 25 percent (wt/wt) for untreated diesel cuttings, 15 percent for treated diesel cuttings and 5 to 10 percent for untreated paraffin cuttings.

TABLE 2-19

RESIDUAL OIL IN CUTTINGS DISCHARGES (North Sea Development Wells)

	CLEANING SYSTEM	OIL CONTENT (Percent)	ANALYTICAL METHOD	REF.
Diesel-Base System	Typical North Sea U.K.	15 (wt.)	-	1
		10-15 (wt.)	-	2
	Diesel and sea water - North Sea Norway	9	IR	3
	Diesel and sea water - North Sea U K	20	Retort	4
	Diesel wash	15	UV	5
	Untreated	29	UV	5
	Single Stage diesel wash	28	UV	5
	Diesel wash	17	UV	5
	Diesel wash	17*	UV	5
Paraffin-Base System	No treatment (coarse solids)	10*	IR	5
		5*	UV	
	No treatment (fine solids)	37	UV	5
	No treatment	5	Retort	6

1 pers. comm. Johnston
2 pers. comm. Davies
3 Grahl-Nielsen et al. 1980
4 pers. comm. T. Sauer
5 Blackman et. al., 1982
6 Chromalloy 1982

* Same field trial, using different mud systems

3.0 Ballast and Storage Displacement Water

3.1 Introduction

Two types of ballast water are found in offshore producing areas. Tanker ballast water comprises sea water or fresh water from the region where ballast was pumped into the vessel. It may be contaminated with crude oil (or possibly some other cargo such as fuel oil) if the vessel does not have segregated cargo and ballast tanks.

Floating platform (storage unit or processing unit) ballast or stabilization water comprises sea water from the area of the producing field, and is generally clean as these platforms have segregated ballast tanks. The oil storage tanks may be required to take on additional ballast in emergency situations, however.

Storage displacement water is the water used to displace crude oil from floating and semi-submersible storage units. This water is only slightly contaminated with oil. The oil and water are not mixed because a constant interface is maintained between the oil and water during loading and withdrawl of oil.

3.2 Storage Capacity and Discharge Rates

Ballast water and storage displacement water discharges are characterized by intermittent flow at high flow rates over a relatively short period (a few hours to a few days). Large storage volumes are required to allow offloading of large tankers. Volumes and discharge rates for tanker ballast water are given in Table 2-20.

Discharge rates for ballast from floating platforms are lower than for tanker ballast. The only value found in a search of literature and available monitoring data was 5,000 m^3/d for a floating storage and processing platform off the coast of California (Exxon Company U.S.A. 1981).

Storage volumes for crude oil (and therefore for storage displacement water when crude oil has been pumped out) at offshore installations in the North Sea are typically 150,000 m^3 and range from 50,000 to 300,000 m^3 (E & P Forum 1982b). When crude oil is pumped into the storage tanks, the water in the storage tanks is pumped out at the same rate (Schreiner 1980). Discharge rates can be high, ranging from 12,000 to 48,000 m^3/d for two North Sea offshore installations (E & P Forum 1982b). Most North Sea tanker loading facilities and attendant ballast discharge takes place at onshore terminals, with discharges to nearshore waters.

TABLE 2-20

TANKER BALLAST WATER DISCHARGE RATES

LOCATION	REF.	STORAGE CAPACITY (m^3)	DISCHARGE RATE (m^3/d)	
			$\bar{X}$	Range
Gulf of Alaska	1	70,000	-	-
Gulf of Alaska	2		55,000	49,000-115,000
North Sea	3 Platform A	125,000	9,600	-
	Platform B	150,000	12,000	-
North Sea	4	170,000	80,000	190,000 (max)
North Sea	5	225,000	87,000	-
North Sea	6	160,000	-	-
Mediterranean Sea	7	30,000	-	96,000-288,000
TYPICAL	-	150,000-200,000	50,000	10,000-200,000

REFERENCES:

1 Lysyj 1981 (Gulf of Alaska, Port of Valdez)
2 U.S. EPA 1982a (Gulf of Alaska, Port of Valdez)
3 Tramier et al. 1981 (North Sea)
4 Jenkins and Reid 1980 (Forties Field, Dalmeny Shore Terminal)
5 Henricksen 1980 (Ekofisk Field, Teeside Shore Terminal)
6 Moore 1980 (North Sea, Claymore Field, Flotta Shore Installation)
7 Marson 1980 (Mediterranean Sea, Sidi Kerir Terminal, Egypt)

3.3 Composition

3.3.1 Tanker Ballast Water

Table 2-21 shows the characteristics of tanker ballast water for a number of onshore and offshore terminals. Ballast water is characterized by total oil concentrations in treated effluent which typically range from 2-15 mg/L and dissolved aromatic concentrations of approximately 5 mg/L. Compared to produced water, untreated ballast water contains considerably higher free oil concentrations (1,000 - 3,000 mg/L vs 200 - 500 mg/L) but treated ballast water contains lower total oil concentrations (10 mg/L vs 40 mg/L). Most dissolved ion concentrations in ballast water are similar to those found in sea water being considerably lower than in produced water (typical TDS of 5,000 to 30,000 mg/L vs 100,000 mg/L).

TOC concentrations in ballast water are considerably lower than in produced water, possibly because organic acids are largely absent in ballast water and because inorganic rather than organic treatment chemicals are largely used (Oldham 1982). Ballast water and produced water typically have relatively high concentrations of aromatic hydrocarbons (3-5 mg/L). The aromatic content of different ballast waters, however, varies widely and can at times be very high, exceeding 10 mg/L. Insoluble oil is removed easily and efficiently by ballast water treatment systems. Dissolved hydrocarbons (aromatic compounds in particular) may be stripped out up to 50% in a gas flotation unit, but are not reduced through simpler gravity separators such as plate interceptors.

Chemicals added to the ballast water during treatment influence the characteristics of the final discharge. No data were available on the concentration of these chemicals in ballast water effluents. The chemicals commonly used and normal dosage are listed in Table 2-22.

Some North Sea shore terminals which treat oily ballast water may also handle pipeline and desalter wash water. Slugs of oily water which come to shore from offshore operations or pipeline pigging, may contain corrosion inhibitors or other chemicals which can cause ballast water treatment plant upsets. Desalter waste waters at shore terminals may contain demulsifiers carried in an aromatic hydrocarbon solvent, causing increased hydrocarbon levels in the ballast treatment effluent (pers. comm. Johnston).

TABLE 2-21

TANKER BALLAST WATER CHARACTERISTICS

PARAMETER	UNITS	REF. 1*		REF. 2*		REF. 3		REF. 4		REF. 5*	
		X̄	Range	X̄	Range	X̄	Range	X̄	Range	X̄	Range
Temperature	°C	-	-	15	11-24						
Density	g/cm³	-	-	-	-						
pH		-	-	6.4	4.8-7.5						
Total dissolved solids	mg/L	-	-	-		-	5,000-30,000				
Total suspended solids	mg/L	-	-	14	9-20						
BOD	mg/L	-	-	23	15-29						
COD	mg/L	-	-	-	-						
TOC	mgC/L	10.7	10.2-10.9	20	6-32						
Total Oil -calculated	mg/L	5.8	4.6-7.1	-							
Oil - GR³	mg/L	-	-	2.3	1.4-8.7						
Oil - IR⁴	mg/L	-	-	-	-						
Total volatile hydrocarbons¹	mg/L	4.9	4.4-5.2	-	-	10	6-13	13	0-35	1.5	0-4
Total dissolved organics²	mg/L	4.3	3.7-5.2	-	-						
Total suspended organics²	mg/L	1.5	0.9-1.9	-	-						
Aliphatic hydrocarbons¹	mg/L	0.2	0-0.2	-							
Aromatic hydrocarbons	mg/L	-	-	7.7	3.4-19.0						
- Benzene¹	mg/L	2.0	1.8-2.3	-	-						
- Toluene¹	mg/L	1.8	1.7-1.9	-	-						
- Xylenelethylbenzene¹	mg/L	0.9	0.7-1.0	-	-						
- Phananthrene/anthracene¹	mg/L	-	-	0.003	0.001-0.01						
- Phenols	mg/L	-	-	0.29	0.18-0.43						
- Methylene chloride	mg/L	-	-	0.068	0.001-0.202						
- Trichloroethylene	mg/L	-	-	0.001	-						
Cadmium (dissolved)	mg/L	-		0.002	0.002-0.003	Data not available. Analyses conducted at North Sea terminals show metal contents reflecting wide range of water sources (pers. comm. Johnston).					
Chromium (total)	mg/L	-		0.004	0.002-0.010						
Copper (total)	mg/L	-		0.030	0.002-0.058						
Lead (total)	mg/L	-		0.009	0.005-0.047						
Nickel (total)	mg/L	-		0.031	0.004-0.220						
Selenium	mg/L	-		0.005	0.001-0.005						
Zinc (total)	mg/L	-		0.914	0.005-6.92						

REFERENCES:

1 Lysyj 1981 (Gulf of Alaska, Port of Valdez)
2 U.S. EPA 1982a (Gulf of Alaska, Port of Valdez)
3 Tramier et al. 1981 (North Sea)
4 Moore 1980 (North Sea Pipe/Claymore Field, Flotta Shore Installation)
5 Marson 1980 (Mediterranean Sea, Sidi Kerir, Egypt)

FOOTNOTES:

1 By gas chromatography
2 By TOC analyzer, Standard Method 510 (8)
3 By gravimetric method
4 By infrared method
* Oil port, not producing field

TABLE 2-22

CHEMICALS ADDED DURING BALLAST WATER TREATMENT

PURPOSE	CHEMICAL	DOSE	FATE	REF.
Coagulant and flocculant	cationic branched polyamine	5 mg/L	mostly into recovered crude oil	1
Demulsifier flocculant	alum ferric salts polyelectrolyte	5 - 150 mg/L 5 - 150 mg/L 1 - 5 mg/L	mostly into recovered crude oil	2
	alum polyelectrolyte	30 - 40 mg/L 0.6 - 1.0 mg/L		3
Bactericide	hydrogen peroxide	20 mg/L		1

1. Lysyj 1981
2. Chappell and Gray 1976
3. Henrickson 1976

Note:

Table is valid for treatment systems handling only ballast water. If pipeline water is also handled (as is the case for a number of North Sea shore terminal ballast facilities) H_2S problems from sour crude and sulphur-reducing bacteria may require use of additional bactericides (pers. comm. Johnston).

3.3.2 Platform Ballast Water

Unlike tanker ballast water, which may have had multiple sources and which may contain added contaminants, platform stabilization (ballast) water is taken on from the waters adjacent to the platform and will, at worst, be contaminated with stored crude oil and platform oily slop water. Newly designed and constructed floating platforms (storage) will probably use permanent ballast tanks which may become contaminated with oil only in emergency situations when excess ballast must be taken on (E & P Forum 1982b). The oily water must be treated through an oily water separation process similar to that used for ballast water or storage displacement water where platforms do not have segregated oil storage and ballast tanks. Therefore, typical oil content in the effluent will be about 10 mg/L (Read 1980).

Bilge water, which seeps into all floating vessels, is a minor waste for floating platforms. This sea water becomes contaminated with oil and grease and with solids such as rust where it collects at low points in vessels. This bilge water is usually directed to the oily water separator system for ballast water or produced water, or discharged directly. Discharge, if direct, is intermittent and totals approximately 1 m^3/d (Shell 1981).

3.3.3 Storage Displacement Water

Storage displacement water from floating or semi-submersible offshore crude oil structures is mainly composed of sea water. Much of its volume can usually be discharged directly without treatment, since little mixing occurs with the oil floating on top of the water. The water which is in contact with the oil can receive a small amount of dissolved aromatic constituents through molecular diffusion at the oil-water interface. Paraffinic compounds have low solubilities in water and will not migrate into water solution to any appreciable degree. Crude oil constituents will not be significantly dispersed in particulate form into the water below, except in unusual circumstances such as very rough seas, because the oil-water interface is always maintained. The interface water is usually treated through an oily water separator system before discharge. Typical oil content in the storage displacement water discharge is 10 mg/L (Read 1980).

While being stored offshore, crude oil contains a small amount of water which has not been separated during processing (produced water separation). Some of this water may separate during storage, and sink to the bottom of the storage tank. A small amount of water similar in composition to production water may mix with the storage displacement water below, or be left behind in the bottom of tanks committed to segregated crude oil storage (E & P Forum 1982b).

It should be noted that natural sea water has relatively high concentrations of major anions such as bicarbonate and sulphate compared with produced water. Storage displacement water and produced water cannot be mixed because this mixture will precipitate metal and salt compounds. As a result these two forms of offshore oily waters must often be treated separately.

In some cases, storage of displacement water may allow the growth of sulphur-reducing bacteria leading to the production of hydrogen sulphide gas (pers. comm. Johnston).

4.0 Produced Sand

Produced sand (sand and clay solids which are brought to the surface and removed from crude oil and produced water) is not analysed for oil or major constituents in most offshore platform discharge studies or regulatory monitoring programs. If low volumes of fine sands are produced, they are drained into drums on deck or are carried through the oily water treatment system and appear as suspended solids in the produced water effluent or drop out in treatment vessels (Maer 1975; Train et al. 1976). If sand volumes are larger and sand particles coarser, the solids are removed in cyclone separators, thereby producing a solid phase waste. The sand which drops out in these separators is generally contaminated with crude oil (oil production) or condensate (gas production) and requires washing to recover the oil (Manning et al. 1974). The sand is washed with straight water, water combined with detergent, or solvents. The oily water is directed to the produced water treatment system or a separate oily water separator and becomes part of the produced water discharge, following oil separation (Train et al. 1976; Pappworth 1979; pers. comm. Holliman). The clean sand is discharged overboard, or occasionally, hauled to shore for land disposal. In some locations (a number of Gulf of Mexico and Cook Inlet platforms) the produced sands are piped to shore with produced water for treatment, separated and disposed on land (Maer 1975).

The oil content of cleaned produced sand before discharge has not been reported in the literature reviewed. Sand which has been treated for oil removal is reported to have no oil adhering to it (Train et al. 1976). One pilot test of a sand washer had a maximum oil content in the sand discharge of 1 mg/L (Garcia 1974).

Produced sand discharges may be continuous or intermittent depending on the volumes produced. Compared with typical maximum produced water discharge rates for the Gulf of Mexico of 4,000-40,000 m^3/d, typical maximum produced sand discharge rates are on the order of 4-40 m^3/d (Maer 1975). One figure for produced sand, which is site-specific and cannot be considered typical, is 1 m^3 sand per 2,000 m^3 oil production (Manning et al. 1974). One general figure for southern California producing fields, which are considered to produce small quantities of produced sand, is 1 m^3/d (Hester 1981). Another estimate is 2 kg/d per well (Mors et al. 1982). Maximum sand discharge rate at the Murchison oil field in the North Sea is reported to be 7 m^3/d (Pappworth 1979).

5.0 Deck Drainage

Deck drainage is rainwater runoff from open platform surfaces plus deck and process equipment washdown water, both of which are contained on the platform by curbs, gutters and drip pans. The decks of offshore platforms must be kept clean to reduce fire hazards and for personnel safety reasons, so deck drainage contains a small amount of detergents and (occasionally) solvents. Small amounts of various lubricating, hydraulic and valve seal oils which drip onto contained deck surfaces are also present.

Deck drainage discharges are intermittent and of short duration, occurring only during incidents of rainfall and when deck or equipment washdowns are performed. The duration of many deck drainage discharges is between 15 minutes and 1 hour (Berry 1980). The discharge rate for deck drainage caused by rainfall is dependent upon the rate of precipitation and the exposed deck area. Typical exposed deck areas and normalized deck drainage rates for a number of Gulf of Mexico platforms are shown in Table 2-23. Table 2-24 gives data for observed deck drainage discharge rates.

Deck drainage flows are composed of fresh or salt water containing various oils, solvent, detergent and solid contaminants. Typical deck wash chemicals are laundry detergents, surfactants and dispersants and, occasionally, solvents such as Varsol. Use rates reported in one study varied from 5 to 2,500 litres per washing (Jackson et al. 1981). Deck drainage discharges are seldom monitored for quality because of the low total loadings of contaminants associated with these discharges. Little information was available for oil concentration of typical deck drainage discharges, following gravity separation. One estimate of oil content of deck drainage following gas flotation treatment is 25 mg/L oil, indicating similar oil levels to produced water effluents (Train et al. 1976). A permit for a Cook Inlet platform shows oil concentrations not to exceed 65 mg/L average and 90 mg/L total (U.S. EPA 1982a).

The nature of oils which will drip onto a platform deck (refined oils with various additives), however, and the fact that detergents and solvents may be mingled with the oil means that deck drainage discharges can be expected to contain emulsified oil. Spilling of drilling mud products, including oil-base mud, and workover and completion chemicals, may cause the occasional deterioration in deck drainage quality (Train et al. 1976). The workover fluids may include hydrochloric, hydrofluoric and organic acids. These are generally neutralized in other deck

TABLE 2-23

DECK DRAINAGE DISCHARGE DUE TO RAINFALL

PLATFORM TYPE	EXPOSED DECK AREA (m^2)	DRAINAGE DISCHARGE/cm RAIN (m^3)
small production	125	1.3
6 pile production	660	6.6
12 pile production	1,050	10.5
8 pile gas production	1,120	11.2
rig	1,200	12.0
4 pile production	1,240	12.4
8 pile oil production	1,400	14.0
20 pile production	1,425	14.3
jackup	2,225	22.3
28 pile production	14,440	144.0
MEAN	2,500	25.0
MEDIAN	1,220	12.2

Source: pers. comm. Burgbacher.

TABLE 2-24

DECK DRAINAGE FLOW RATES

LOCATION	REFERENCE	SOURCE OF FLOW	m^3/d	NATURE OF FLOW
California	Hester 1981	deck wash	0.1 (typical)	intermittent, not daily
Cook Inlet	U.S. EPA 1982a		0-1,500; 76 mean	-
Gulf of Mexico	Jackson *et al.*, 1981	rainfall	330 (single event)	single, heavy flow
Gulf of Mexico	Maer 1975	drains and sumps	0.3-4	likely excludes rainwater runoff
North Sea	Schreiner 1980	total deck drainage	550 average	-

drainage liquids before discharge (Mors et al. 1982). Total oil discharges are likely to be small. One estimate based on a survey of 23 U.S. platforms is less than 0.25 litres per day discharge of oil and grease in deck drainage flow (Berry 1980).

6.0 Well Completion and Workover Fluids and Miscellaneous Well Fluids

A number of chemical fluids and inert solids are used to complete a production well and to work it over at various times. These additional wastes associated with oil and gas producing wells are described below.

(a) Completion fluids: salt solutions, acids and various drilling fluid additives used to improve the flow of hydrocarbons from the formation and to prevent damage to the well bore during operations which prepare the drilled well for hydrocarbon production (Hester 1981). These fluids move into the formation and return to surface with produced water.

(b) Packer fluids: a mixture of a polymer viscosifier, a corrosion inhibitor and a high-concentration salt solution. This mixture is set permanently between the well casing and the flow tubing, just above the production zone (hydrocarbon reservoir) during well completion (Gray *et al*. 1980). These fluids remain in the hole and are returned to surface during well workover.

(c) Well workover fluids: various acid solutions, solids and specialty chemicals used for increasing the producing capacity of a well after it has been operating for a number of years, or to re-open a "shut-in" well (Mors *et al*. 1982). The fluids move into the formation and return to surface with produced water.

(d) Blowout preventer (BOP) fluid: an oil (vegetable or mineral) or antifreeze solution (glycol) used as a hydraulic fluid in BOP stacks during drilling of a well (Hester 1981, ESL 1982). BOP fluid is discharged periodically to the sea floor during testing of the blowout preventer device.

(e) Excess cement: slurry of cement, water and some drilling fluid used to cement well casing into the formation rock (Hester 1981). A portion of this cement is released to the sea bottom as excess.

See Table 2-25 for a description of the composition, handling and fate of the various well fluids defined above.

TABLE 2-25

PROPERTIES OF COMPLETION, WORKOVER AND MISCELLANEOUS WELL FLUIDS

FLUID TYPE	TYPICAL CONSTITUENTS	DOSAGE/VOLUME	FATE	COMMENTS	REF.
Completion Fluids					
(1) Clear fluids (high density from from 1.2-2.3 g/cm^3)	Calcium chloride Calcium bromide Calcium fluoride Zinc bromide Ammonium chloride Potassium chloride	up to 80 m^3 may return to surface, per well	Migrate into formation and return to surface as a slug in produced water; as much as possible is recovered at surface because of high cost	Slug of salt solution may upset oily water separation and cause short-term upset and high oil in effluent	(1,2,3,4)
Viscosifiers and filtrate control	Hydroxyethyl cellulose Xanthum gum Calcium carbonate	10-40 kg/m^3 fluid	-	-	
Corrosion inhibitors	Amines	10-40 kg/m^3 fluid	-	-	
Biocides	Paraformaldehyde				
Defoamers	Alkylalcohols Sulfonated vegetable oils	0.3 kg/m^3	-	-	
(2) High solids fluids	Combination of drilling mud additives; calcium and iron carbonate may also include diesel oil (North Sea)	-	Return to surface with drilling fluids	-	(3)
(3) Mud Acidifiers	Hydrofluoric acid Fluorosilicates Hydrochloric acid (HCl:HF = 4:1)	up to 150 m^3 per well drilled	Migrate into formation and return to surface in produced water; some may come to surface with drilling fluids; returned acid largely spent and therefore in salt form; HF may not be all spent	May upset oily water treatment system	(7,8,11)
Packer Fluids					
Clear fluids	Sodium chloride Sodium carbonate Calcium chloride Calcium bromide Zinc bromide	Few m^3 total fluid	Return to surface with produced water before well work-over, in a slug; as much as possible is recovered	Slug of salt solution may upset produced water oily water separator and cause high oil content in effluent for few hours	(1,5,6)
Viscosifier	Various natural polymers as for completion fluids				
Sealing material	Asbestos or other particulate solid				
Biocide	Chlorinated phenols (prohibited in U.S. and U.K.)				
Corrosion inhibitor	Amines				
Workover Fluids					
(1) Formation acidizing fluids	Hydrochloric acid (15%) Hydrofluoric acid Acetic acid	-	Migrate into formation and return to surface with produced water as a slug; acid mostly spent, although some HF may not be completely dis-associated	Slug of spent acid may upset produced water oily water separator and cause high oil content in effluent (up to 300 mg/L), for period of few hours.	(4,7,8,11)
Corrosion inhibitor					
Demulsifier					
			In North Sea, may pass down oil pipeline to shore treatment.	Slug of workover fluid may upset shore treatment facility.	
Diverting Agents	Resins Benzoic acid Paraffins				
(2) Fracturing fluids	Liquid carbon dioxide and nitrogen Cellulose, guar gum natural polymers Cellulose enzymes Ammonium persulfate Crude oil, kerosene	-	Migrate into formation; some return to surface with produced water and sand	-	(7,11)
BOP Fluid	Biodegradable vegetable oil (California, North Sea)	Daily to weekly release	Released into water at sea floor	-	(3,9,10,12)
	Ethylene glycol (Beaufort Sea)	0.02 - 1.0 m^3 each release 140 m^3/well			
Excess Cement	Portland cement (lime, silica and water) Calcium oxide Di- and tri-calcium silicate Tricalcium aluminate Tricalcium alumino-ferrite Traces of magnesia, alkalies and sulphur trioxide	2-4 times during drilling of each well, 3-23 m^3 discharge	Discharged into water at sea floor	-	(3,9,10)

Sources:

(1)	Gray et al. 1980	(7)	Maar 1975
(2)	pers. comm. J. Swiss	(8)	pers. comm. Swiss, Laut and Thomas
(3)	Mors et al. 1982	(9)	Nestor 1981
(4)	pers. comm. Castle	(10)	ESL 1982
(5)	Jackson et al. 1982	(11)	Langer 1981
(6)	Hall 1982	(12)	pers. comm. Johnston

7.0 Sanitary and Domestic Wastes

Sanitary wastes (black water) consist of human wastes only, as defined for offshore platforms. Domestic wastes (grey water) comprise liquid kitchen wastes, shower and wash water and laundry wastes.

The results of a few monitoring programs and surveys which have been carried out in U.S. offshore production areas show that sanitary waste discharge rates from offshore platforms range from 4-15 m^3/d, with the lower value being more typical. Typical combined domestic and sanitary discharge rates are about 10 m^3/d.

Sanitary and domestic waste flow rates and characteristics are well known and can be easily predicted using engineering rules of thumb based on m^3/capita/day discharge rates and kg/capita/day for constituent loadings (See Table 2-26). Domestic wastes contain relatively high BOD and suspended solids levels, and soap and detergent at unknown concentrations.

Domestic solid waste (garbage) generation has been estimated to be 0.25 m^3/day for offshore platforms in the Gulf of Mexico (Maer 1975). Another estimate is 900 kg/d for one platform (Dome Petroleum et al. 1982 Vol. 4). These wastes include various sludges, paper and metal wastes. A domestic solid waste production rate of 3.6 kg/capita/day has been estimated for a Beaufort Sea production shorebase (Dome Petroleum et al. 1982 Vol. 2). Approximately 85 percent of this waste would be combustible.

TABLE 2-26

TYPICAL OFFSHORE SANITARY AND DOMESTIC WASTE CHARACTERISTICS

		LOADING		CONCENTRATION		
	DISCHARGE RATE (m^3/cap/day)	BOD (kg/cap/day)	S.S (kg/cap/day)	BOD (mg/L)	S.S (mg/L)	RESIDUAL CHLORINE (mg/L)
Sanitary waste (treated)	0.075 (1)	0.002(3)	0.003(3)	30	40	1.7
Domestic waste (direct discharge)	0.11 (1)	0.022(2)	0.016(2)	195	140	0

Sources:

(1) Adapted from Hooper and Myrick 1971
(2) Adapted from Manning et al. 1974
(3) Adapted from Train et al. 1976

8.0 Oil and Gas Processing Wastes

Oil and gas processing wastes are defined in the context of this report as liquid and solids wastes produced by the offshore (platform-based) processing of produced oil and gas. Gaseous emissions from this processing, and onshore treatment beyond simple dehydration and desalting, are excluded from this analysis. The liquid processing wastes on an offshore platform are usually directed to sumps from which oil is recovered and water is directed to the produced water or the deck drainage system. Solid processing wastes (including sludges) are incinerated or hauled to shore for treatment.

Gas processing wastes derive mainly from dehydration of the produced gas. These liquid wastes contain ethyleneglycol or diethyleneglycol. The chemicals are lost to sumps at low rates through leakage and process drains. Glycol losses are about 8 kg/d for a facility processing 1 million m^3/d gas and 82 kg/d for a 10 million m^3/d facility (based on typical onshore dehydration facilities).

Oil processing wastes derive mainly from produced brine separation from crude oil. The oily brines separated during this process become part of the produced water treatment system containing residual crude oil and other organic materials (Montreal Engineering Company Limited 1981).

Waste oils and sludges are produced during the treatment of processing wastes and produced water. In the Gulf of Mexico and Cook Inlet, recovered oil and foam, floc and suspended particles are directed to the crude oil process system, thereby allowing recovery of the product (Train et al. 1976). Another approach used for treatment systems which have high added treatment solids levels (clay) is to haul the recovered oily solids (sludge) to shore for burial. In one such situation, 10 m^3/d sludge is generated from a 2,240 m^3/d produced water treatment system (Train et al. 1976).

Other sources of sludges include corrosion products and recovered oily waste from settled deck drainage, tank bottoms, and crude oil dehydrator and produced water separator underflows (Manning et al. 1974; Montreal Engineering Company Limited 1981). One estimate of the volume of sludge produced is 32 m^3/d for a 32,000 m^3/d crude oil producing facility. Platforms which inject produced water, produce sludges from the filtration systems used to treat the water before injection. These sludges are normally hauled to shore.

9.0 Miscellaneous Discharges

A small number of miscellaneous minor wastes is produced on offshore oil and gas production platforms. These are:

(a) Desalination waste: the residual high-concentration brine discharged from distillation or reverse-osmosis units used for producing potable water and high quality process water offshore (Hester 1981). Its chemical composition and ratio of major ions is the same as for sea water, but with higher concentration. This waste is discharged directly to the sea (Hester 1981; Exxon Company U.S.A. 1981).

(b) Cooling water from offshore platforms: non-contact, once-through water used to cool crude oil, produced water, power generators and various pieces of machinery (Hester 1981). It is composed of sea water and occasionally an algicide. The temperature of these discharges may be high compared to that of the receiving water (pers. comm. Johnston).

(c) Fire control system test water: sea water, treated with an algicide. It is discharged periodically, during tests, directly to the sea (Exxon Company U.S.A. 1981).

A description of the composition and handling of these minor wastes is given in Table 2-27.

TABLE 2-27

PROPERTIES OF MISCELLANEOUS OFFSHORE PRODUCTION WASTES

WASTE TYPE	COMPOSITION	VOLUME	HANDLING	REF.
Desalination Brine				
reverse osmosis reject (potable and boiler water treatment)	Chloride 27,000 mg/L Sodium 15,000 mg/L Sulphate 3,800 mg/L TDS 49,000 mg/L	-	Direct discharge overboard	(1)
reverse osmosis reject (potable water only)	TDS = 1.15 x sea water bisulphite added as biocide	20 m^3/d (several 1000 gpd)	Continuous or intermittent direct discharge overboard	(2)
distillation (producing 65 m^3 potable and process water)	TDS = 2 x seawater TSS = 28 mg/L* pH = 7.35* COD = 1,125 mg/L* Residual chlorine <0.1 mg/L Temperature increase <11°C	33 m^3/d	Mixed with cooling water and discharged to surface	(3)
Cooling Water				
California production platform	Sea water Temperature increase <11°C	450 m^3/d (several thousand gph)	Direct discharge to the sea surface	(2)
California processing and storage platform	Sea water Temperature increase <11°C Residual chlorine 0.5 mg/L TSS = 28 mg/L pH = 7.35 COD = 1,125	10,500 m^3/d	Mixed with desalination waste and discharged to surface	(3)
North Sea (Murchison)	Sea water	67,000 m^3/d	Diluted with 65,000 m^3/d sea water from firewater system and discharged to sea surface	(4)
Fire Control Test Water				
California	Sea water Ambient temperature	10 m^3 (few thousand gallons)	Discharge once per week	(2)
California	Sea water Chlorine disinfectant	80 m^3/d	Intermittent discharge	(3)
North Sea	Sea water	65,000 m^3/d	Continuous discharge	(4)

* Mixed with 10,500 m^3/d cooling water

Sources
(1) Montreal Engineering Company Limited 1981
(2) Hester 1981
(3) Exxon 1981
(4) Pappworth 1979
(5) Train et al. 1976

CHAPTER 2

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CHAPTER 2

PERSONAL COMMUNICATIONS

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B. Thomas. Dome Petroleum Limited. Calgary, Alberta.

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CHAPTER 3

DISCHARGE AND DISPOSAL PRACTICES

1.0 Current Practice

The majority and largest volume of wastes produced at offshore oil and gas platforms are discharged directly to waters surrounding the platform, usually with some form of treatment before discharge. Some nearshore facilities or those in sensitive areas may pipe or haul wastes to shore for treatment and subsequent disposal on land, into coastal waters or into the ground by injection. Figure 3-1 summarizes the waste discharge and disposal practices currently in use. Tables 3-1 to 3-4 compare disposal methods used for various wastes in different areas of the U.S. and the North Sea.

FIGURE 3·1
METHODS FOR DISCHARGE/DISPOSAL OF OFFSHORE PRODUCTION WASTES

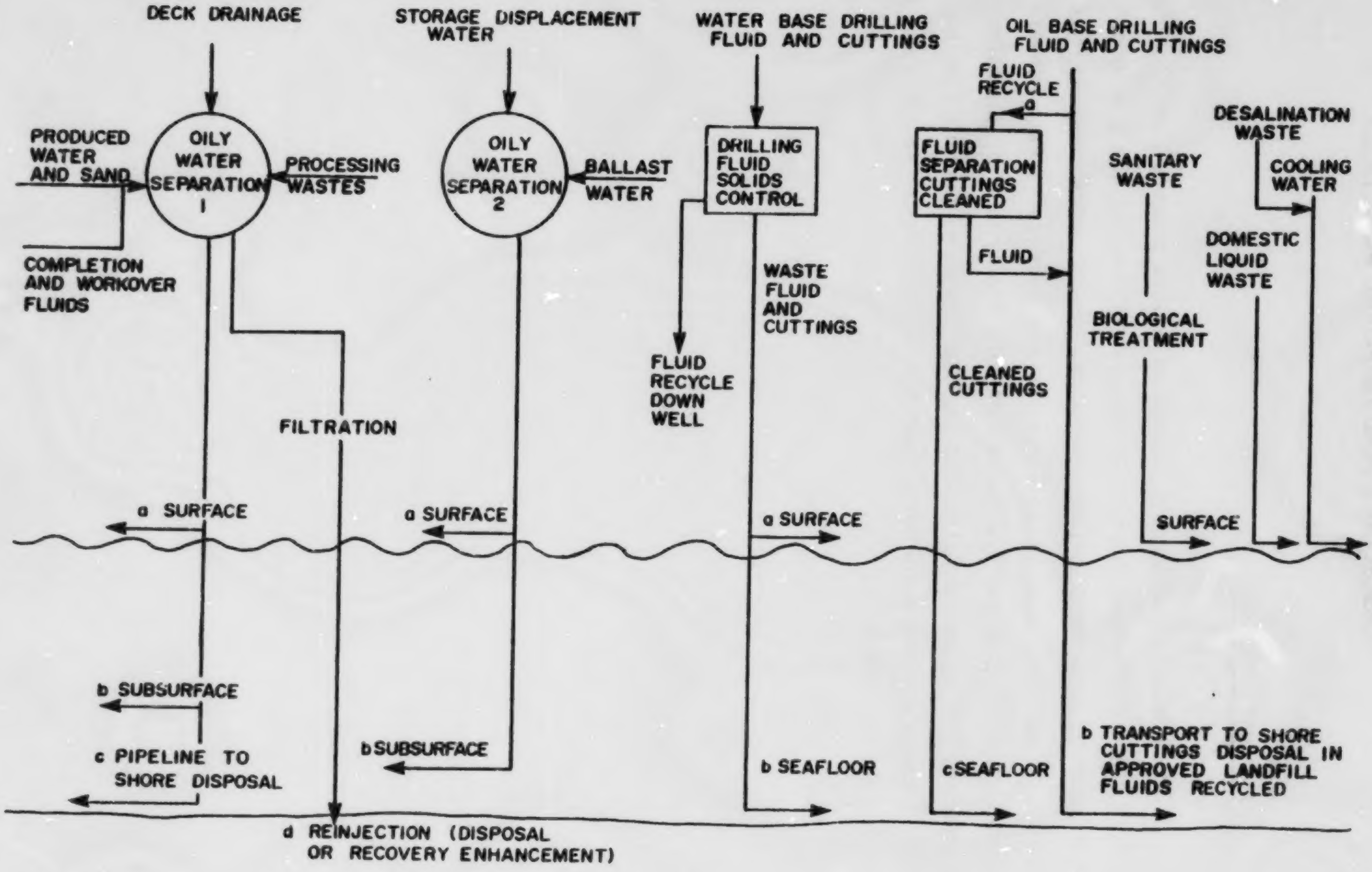
DECK DRAINAGE
STORAGE DISPLACEMENT WATER
WATER BASE DRILLING FLUID AND CUTTINGS
OIL BASE DRILLING FLUID AND CUTTINGS
FLUID RECYCLE
a
PRODUCED WATER AND SAND
OILY WATER SEPARATION 1
PROCESSING WASTES
OILY WATER SEPARATION 2
BALLAST WATER
DRILLING FLUID SOLIDS CONTROL
FLUID SEPARATION CUTTINGS CLEANED
DESALINATION WASTE
SANITARY WASTE
COOLING WATER
COMPLETION AND WORKOVER FLUIDS
FLUID
DOMESTIC LIQUID WASTE
WASTE FLUID AND CUTTINGS
BIOLOGICAL TREATMENT
FLUID RECYCLE DOWN WELL
CLEANED CUTTINGS
FILTRATION
a SURFACE
a SURFACE
a SURFACE
SURFACE
b SUBSURFACE
b TRANSPORT TO SHORE CUTTINGS DISPOSAL IN APPROVED LANDFILL FLUIDS RECYCLED
c PIPELINE TO SHORE DISPOSAL
b SUBSURFACE
b SEAFLOOR
c SEAFLOOR
d REINJECTION (DISPOSAL OR RECOVERY ENHANCEMENT)

TABLE 3-1

SUMMARY OF PRODUCED WATER DISPOSAL METHODS

LOCATION	PREDISCHARGE TREATMENT METHOD	TYPICAL DISPOSAL/ DISCHARGE METHOD	OTHER DISCHARGE METHODS
California	Almost all platforms pipeline produced water to shore for treatment (1)	Onshore injection for disposal (1,7)	Emergency methods if treatment equipment breaks down 1) discharge over board, 2) discharge to sunken pile
Gulf of Mexico		From pipe on platform above water surface or via skim pile or sump pile to mid depth (2,5,6)	Reinjection for pressure maintenance or water flooding (1)
Cook Inlet	Most pipeline produced water to shore for treatment (3)	Pipeline from shore-based treatment facility to near-shore outfall (3)	No injection. Sea water used for flooding. Some offshore discharge from skim tanks (1,3)
North Sea		Sea sump or caisson up to 1.5 m diameter typically to mid-sea depth, may be 10's of metres (4)	Some injection for disposal or transport to shore by crude oil pipeline (8)

REFERENCES

(1) Train et al. 1976
(2) Mors et al. 1982
(3) Lysyj 1982
(4) E & P Forum 1982
(5) pers. comm. Burgbacher
(6) pers. comm. Richerand
(7) Langer 1981
(8) pers. comm. Johnston

TABLE 3-2

SUMMARY OF WATER-BASE DRILLING FLUIDS AND CUTTINGS DISPOSAL METHODS

LOCATION	TYPICAL DISPOSAL/ DISCHARGE METHOD	ALTERNATIVE DISCHARGE METHOD
California	Discharge above (3 m) or slightly below (12 m) water surface. Discharge pipes approx. 30 cm inside diameter (1,2)	Transported to shore-base dump site if "generic type" mud not used (9)
Gulf of Mexico	Most platforms discharge just below surface (3 m) or above surface (4)	In areas adjacent to coral reefs shunting to 10 m above sea floor required
Cook Inlet	Vertically oriented 50 cm diameter pipe 15 m below water surface (3)	Dilution may be required before disposal up to (25:1) (5)
Mid-Atlantic	Shunted to 12 m below the surface in 25-cm diameter pipe. One well was required to dilute whole mud 10:1 before discharge. (5,6)	
North Sea	Shunted to 75 m below surface through 46 cm pipe (7); wash fluids to surface (11)	
Beaufort Sea	Diluted and discharged below ice into sea-floor borrow pit, just below surface, or to artificial island shoreline (8, 10)	

REFERENCES WATER-BASED MUDS

(1) Ray and Meek 1980
(2) Benech et al. 1980
(3) Houghton et al. 1980
(4) Ayers et al. 1980b
(5) OOC 1981
(6) Ayers et al. 1980a
(7) pers. comm. King
(8) Friesen 1980
(9) pers. comm. Feole
(10) pers. comm. Psutka
(11) pers. comm. Johnston

TABLE 3-3

SUMMARY OF OILY CUTTINGS DISPOSAL METHODS

LOCATION	TYPICAL DISPOSAL/ DISCHARGE METHOD
Gulf of Mexico	Fluids recycled in shore-based facility, not discharged. Cleaned cuttings shunted to sea bottom
California	All fluids and cuttings transported to shore. Cuttings disposal in Class 1 Dump and fluids recycled.
North Sea	Cleaned cuttings shunted to various depths, from near surface to near bottom. Used oil-base muds shipped to shore.

REFERENCES

pers. comm. Lapinski
pers. comm. Johnston

NOTE

See Chapter 4 Section 1.2.2 for methods used to handle oil-base muds.

TABLE 3-4

SUMMARY OF DISPOSAL METHODS FOR OTHER WASTES

LOCATION	TYPICAL DISPOSAL/ DISCHARGE METHOD	ALTERNATIVE DISCHARGE METHOD
DECK DRAINAGE		
Gulf of Mexico	Included with produced water disposal usually above water surface or below surface through sump pile or skim pile to prevent surface sheen (6)	Segregation of deck drainage flow into separate oily water separator and effluent discharged overboard
California	Combined with produced water (and possibly grey water) and injected for disposal. Filtered solids hauled to shore for disposal.	Segregated flow, oil separation and discharge overboard
Cook Inlet	Discharged from platform (1)	
North Sea	Discharge from above water surface or to sea sump (caisson) at mid sea depth (40-70 m) (3,8)	
BALLAST WATER		
California	Discharged overboard	
Gulf of Alaska	Shore treatment and near-shore disposal (1)	
North Sea	Most platforms use on shore treatment facilities and near-shore disposal e.g., 1. Dalmeny - 70 cm outfall to 300 m offshore (8); 2. Flotta - outfall to 50 m depth in open channel (9)	Some offshore disposal either discharged to surface or below via caisson or skim pile (3,9)

TABLE 3-4 (continued)

SUMMARY OF DISPOSAL METHODS FOR OTHER WASTES

LOCATION	TYPICAL DISPOSAL/ DISCHARGE METHOD	ALTERNATIVE DISCHARGE METHOD
COOLING WATER		
Gulf of Mexico	Discharge above water surface (6)	
California	Discharge above or just below water surface (7)	
SLUDGE		
Gulf of Mexico	Treated sewage sludge dumped overboard. Oily sludge transported to shore (2,4)	
California	Oily sludge from produced water treatment facilities to approved land disposal (1)	
PRODUCED SAND		
California	Piped or barged to shore with produced water for separation and disposal in approved landfill sites (1)	Separation may occur on platform and clean sand discharged offshore (1)
Gulf of Mexico	Cleaned or untreated sand dumped overboard (1)	
SOLIDS		
U.S. and North Sea	General practice is to transport plastics, glass, metals to a shore landfill site in containers	

TABLE 3-4 (continued)

SUMMARY OF DISPOSAL METHODS FOR OTHER WASTES

LOCATION	TYPICAL DISPOSAL/ DISCHARGE METHOD	ALTERNATIVE DISCHARGE METHOD
SANITARY WASTE		
California	Just above the water line	
Gulf of Mexico	Discharged overboard (4)	
Cook Inlet	Discharged overboard (1)	Not discharged - electric toilet (10)
North Sea	Discharged overboard (8)	
DOMESTIC WASTE		
U.S.	Discharged just above or below water line (1)	

REFERENCES

(1) Train *et al*. 1976
(2) pers. comm. Caudle
(3) Schreiner 1980
(4) Mors *et al*. 1982
(5) Manning *et al*. 1974
(6) pers. comm. Burgbacher
(7) Exxon 1981
(8) Jenkins and Reid 1980
(9) Moore 1980
(10) U.S. EPA 1982
(11) OOC 1981

2.0 Technical and Cost Evaluation of Alternative Methods

Produced water and drilling fluids and cuttings are produced in sufficient quantities that the input of contaminants from these wastes are of sufficient concern to warrant evaluation of alternative disposal methods. Ballast water discharges are not considered in this evaluation because: (1) they are normally handled at shore installations; (2) ballast water discharges associated with offshore production are being reduced as segregated ballast tankers come into use; and, (3) there is no information in the literature on alternative disposal methods.

2.1 Disposal of Produced Water

There are several methods for disposal of produced water currently in use, as shown in Table 3.1: surface ocean discharge, subsurface ocean discharge, pipeline to shore for coastal discharge, and injection into a formation. Table 3-5 presents an evaluation of these methods. All methods are technically feasible, but some may be impractical depending on the particular conditions of the producing region.

One method, injection into a formation, has been the subject of considerable evaluation in the United States as an alternative to surface ocean discharge, which is most commonly practised. The technical feasibility of this disposal method has been shown in a recent evaluation prepared for the U.S. E.P.A. (Langer 1981) and by the fact that a limited number of Gulf of Mexico offshore production facilities and most California offshore production facilities inject produced water for disposal purposes. The E.P.A. study concluded that for new offshore sources of produced water:

(1) California	The injection of brines offshore is practised routinely, "suitable disposal formations with adequate permeability, porosity, thickness and aereal extent are expected to be available" and engineering factors such as availability of pretreatment technology for offshore platforms, transport to shore and onshore disposal of treatment solids and sludges can be accommodated.
(2) Gulf of Mexico	Suitable offshore "disposal formations are generally expected to be available", "a suitable disposal formation may not be available at each and every offshore structure", "it is technically feasible to assure constructability and trouble-free operation of reinjection wells", and pretreatment involving gravity separation, gas flotation and possibly filtration will be necessary prior to reinjection (Langer 1981).

TABLE 3-5

EVALUATION OF METHODS FOR DISPOSAL OF PRODUCED WATER

METHOD	RATING	ADVANTAGES	DISADVANTAGES
surface ocean disposal	feasible and adequate in most situations	low cost; simple to operate	no backup oil skimming in case of treatment plant upset
subsea disposal through sea sump (sump pile)	feasible alternative to surface disposal	simple to operate; moves oily water to depth in case of treatment plant upset and helps prevent formation of surface sheen	increased capital cost over surface disposal
subsea disposal through skim pile	feasible	simple to operate; provides backup oil skimming capability in event of treatment plant upset and helps prevent formation of surface sheen	increased capital cost; increased operating cost for occasional flushing of sludge
pipeline to shore and coastal outfall discharge	feasible for nearshore platforms in shallow water	reduced space and treatment equipment requirement on platform	only feasible for nearshore;[1] reduced natural dispersal in nearshore, shallow water may cause environmental effects or require higher level of oil removal prior to discharge
injection into formation	impractical to feasible, depending on platform and field age, location, size, produced water flow rates	no ocean discharge of oil from produced water	high capital and operating costs; increased downtime for disposal well rehabilitation; deck drainage must be segregated from produced water to prevent bacterial and chemical (oxygen) corrosion of injection wells; solids produced in treatment prior to injection must be hauled to shore for disposal; increased bacterial activity in formation; dependent on availability of suitable formation to accept waste.

Source: Adapted from OOC 1974.

Note 1: At some North Sea platforms, produced water is transported with crude oil by pipeline to shore terminal for separation, treatment and disposal.

Notwithstanding the technical feasibility of produced water injection, an industry study found that the incremental costs for constructing and operating produced water injection systems on offshore Gulf of Mexico platforms were large and would exceed the costs of operating oily water separation systems and surface ocean discharge. Tables 3-6 and 3-7 show the incremental capital and operating costs of injection for three typical produced water discharge rates.

2.2 Disposal of Drilling Fluids and Cuttings

It was concluded in a recent study by the U.S. industry Offshore Operators Committee that only three methods are practical for disposing of drilling fluids and cuttings in the Gulf of Mexico and Georges Bank:

(1) Direct discharge to the surface: an adequate method for disposal of water-base drilling fluids and cuttings in most cases.

(2) Shunting to bottom: a feasible disposal method, but the additional cost imposed by the method means that it should only be used in sensitive biological areas.

(3) Dilution before discharge and surface discharge: feasible and inexpensive, but has no large advantage over undiluted surface discharge because dispersion and dilution of undiluted fluids and cuttings is rapid and occurs over short distances (OOC 1981).

An assessment of methods evaluated in this study and others is presented in Table 3-8 and a cost evaluation of alternative methods is given in Table 3-9.

Haulage of water-base mud to shore for disposal or for re-use was evaluated as being impractical in the OOC (1981) study and by another author (Berry 1981). Oil-base muds from offshore drilling are hauled to shore (in all cases) and re-used (in most cases) because of the high cost of these mud systems (10 to 30 times that of conventional water-base muds) and because oil-base mud disposal in offshore waters is prohibited in most jurisdictions. Oiled cuttings and, in some cases, water-base fluids and cuttings are hauled to shore in some U.S. state waters (Anonymous 1982).

TABLE 3-6

INCREMENTAL CAPITAL COSTS FOR PRODUCED WATER INJECTION

	CASE 1	CASE 2	CASE 3
Facility Design Capacity - Maximum (m^3/d)	1,600	3,200	6,400
Number disposal wells	2	3	5
COSTS	$	$	$
Water Treatment and Pump Plant	7,275,000	10,250,000	15,713,000
Additional Deck or Platform (based on approx. 75 m water depth)	4,000,000	4,000,000	4,000,000
Disposal Wells	2,025,000	3,038,000	5,063,000
TOTAL PER FACILITY	**$13,300,000**	**$17,288,000**	**$24,776,000**

Source: Adapted from OOC (1974)

Note 1: Cost is based on an assumption that 3 out of 4 facilities will involve the addition of another deck level and that 1 out of 4 will involve a separate additional platform installation to accommodate the subsurface water treatment and disposal.

Note 2: Costs are incremental over produced water treatment to meet 72 mg/L oil in surface ocean discharge.

Note 3: All costs in $CDN 1983

Note 4: Cost conversion factor ($US 1974 to $CDN 1983) of 2.5 used to convert data from original source, based on a cost escalation factor of 2.00 and a currency conversion factor of 1.25.

TABLE 3-7

INCREMENTAL OPERATING COSTS FOR PRODUCED WATER INJECTION

	CASE 1	CASE 2	CASE 3
Design Rate m^3/d	1,600	3,200	6,400
Average Flow m^3/d	530	1,070	2,130
COSTS	**$**	**$**	**$**
Well Repair and Reconditioning	150,000	225,000	375,000
Chemical Treatment	15,000	30,000	55,000
Pump and Prime Mover	72,500	165,000	327,500
General Facilities	282,500	322,500	397,500
Solids Handling	15,000	30,000	62,500
TOTAL DIRECT OPERATING AND MAINTENANCE COST	**$535,000**	**$772,500**	**$1,217,500**

Source: Adapted from OOC (1974)

Note 1: Direct operating and maintenance costs only: does not include depreciation, administrative overhead, insurance, taxes and the cost of money.

Note 2: Costs are incremental over produced water treatment to meet 72 mg/L oil in surface ocean discharge.

Note 3: All costs in $CDN 1983

Note 4: Cost conversion factor of 2.5 used from original source data.

TABLE 3-8

EVALUATION OF METHODS FOR DISPOSAL OF DRILLING FLUIDS AND CUTTINGS

METHOD	RATING	ADVANTAGES	DISADVANTAGES
direct surface discharge	feasible and adequate, since rapid dispersion/dilution achieved upon discharge	low cost; no modifications required to conventional solids handling equipment	-
shunting	feasible alternative to surface discharge for drilling adjacent to sensitive environments (e.g., coral reef, sensitive banks)	deposition of material restricted to small area; low-cost alternative	additional cost not required for non-sensitive environments
dilution and direct surface discharge	feasible	dilution of toxic substances prior to discharge; low-cost alternative	need for prior dilution is disputed, since rapid dispersion and dilution occur upon discharge
transportation to ocean dump site	impractical; technically possible	eliminates discharge to sensitive environments	requires additional offshore storage on platform or barge; barges restricted by sea-state; high seas (2 m) cause downtime (stoppage of drilling); attending barge may present safety problem; high cost; difficulty in obtaining permits for ocean dumping site[1]
transportation to land disposal site	feasible to impractical depending on cost, sea-state, available land disposal sites, and distance to shore[2]	eliminates discharge to sensitive environments	same problems of logistics, down time, cost, safety as above; difficulty in finding suitable land disposal sites; inappropriate use of secure landfill sites for a non-hazardous waste
offloading to a single-point mooring (SPM) buoy and transportation by vessel to ocean or land	impractical; technically possible	improved safety over attendant barge for collecting wastes; lower rig downtime (and lower cost)	high capital cost; high operating cost; same problem as above with finding suitable disposal site
pipeline from rig to ocean dump site	impractical; technically possible	allows movement of waste discharge away from sensitive area	environmental effect of pipeline laying; navigation hazard (temporary) line break stops drilling; high capital and operating cost
incineration	not feasible; volatile material content is too low in water-base mud[3]	no advantage for cuttings	considerable incombustible residue must be disposed
injection into formation	not feasible; very high injection pressure required; formation plugging due to viscous properties of fluids; not possible for cuttings	-	high capital and operating cost
recycling	impractical (to feasible); does not eliminate need for disposal of cuttings nor for mud tank dumps at mud changeover	reduces continuous discharge of mud during drilling; reduced mud dilution and use of weighting agent	requires extra space on rig for recycling equipment; additional cost for recycling equipment
reuse	impractical for water-base mud; does not eliminate cuttings discharge nor continuous mud discharges during drilling[4]		for use in new well, reused mud must be diluted due to formation solids (fine cuttings) content; therefore greater volume of fluid; storage capacity and transportation offshore is required between wells; cost involved in above; physical properties of mud may change during storage
shore pit encapsulation	impractical	-	high haulage cost to shore; offshore storage capacity required; difficult to find and receive approval for coastal pit sites

SOURCES
pers. comm. Ayers
Berry (1981)
OOC (1981)
Nesbitt and Sanders (1981)
Anonymous (1982)

Definitions (After Berry 1981)
Feasible: technically possible, safe and reasonable cost
Impractical: technically possible; may have technical problems, potential safety problems or excessive cost

(1) OOC (1981) estimated 12 percent downtime on average for a semi-submersible drilling rig in Baltimore Canyon Atlantic Coast; higher for winter drilling on Georges Bank; 2 percent downtime for Gulf of Mexico

(2) Evaluation by OOC (1981) and Berry (1981), largely based on cost and logistical problems (finding acceptable land disposal site). State of Alabama has prohibited discharge of drilling muds and cuttings in state coastal waters and the industry has responded by collecting and hauling all such wastes to shore for land burial (Anonymous 1982).

(3) Oil-base muds are incinerated and residue hauled to shore at some North Sea locations

(4) Oil-base muds are collected and transported to shore for reuse in the North Sea and to a limited extent in the Gulf of Mexico.

TABLE 3-9

COMPARISON OF COSTS FOR DRILLING FLUIDS DISPOSAL METHODS

METHOD	LOCATION	CONDITIONS	COST ($)
direct surface discharge	all offshore locations	normal drilling practice	no incremental cost
shunting to mid-depth or sea floor	Gulf of Mexico	3,000 m well	126,000 capital, min. operating
	Georges Bank	5,500 m well	126,000 capital, min. operating
dilution	Gulf of Mexico	3,000 m well	7,000 capital, min. operating
	Georges Bank	5,500 m well	7,000 capital, min. operating
transportation to ocean dump site	Gulf of mexico	3,000 m well; 20 days; calm water (2 percent downtime)	238,000
	Georges Bank	5,500 m well; 100 days; 12 percent downtime	4,228,000
transportation to land dump site	Gulf of Mexico	same as for ocean dump site	336,000
	Georges Bank	same as for ocean dump site	4,606,000
pipeline to ocean dump site	Gulf of Mexico	17 km, 25 cm line	14,700,000 (1)
recycling	Gulf of Mexico	mud tanks and cuttings still discharged	19,600 (1) (980/d)
land disposal (excluding haulage costs)	Gulf of Mexico	-	8 to 84/m^3 (2)

Notes: (1) Normal rig operating (drilling) cost/well: Gulf of Mexico 2,800,000
Georges Bank 19,600,000

(2) All costs in $CDN 1983
(3) Cost conversion factor ($US 1981 to $CDN 1983) of 1.4 used

Source: All values adapted from OOC (1981) unless footnoted

(1) Berry 1981
(2) pers. comm. Grubbs

CHAPTER 3

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CHAPTER 4

TREATMENT TECHNOLOGY

1.0 Existing Treatment Technologies

1.1 Oily Water Wastes

1.1.1 Produced Water and Sand

Reservoir fluid (oil or gas) mixed with water and sand (to a much lesser extent) flows through a producing well to a production platform located at the surface. The produced water has its origin either in the formation or from water injected into the reservoir to maintain pressure and oil flow. Water and sand are frequently separated from the reservoir fluid on the production platform, although the production stream is sometimes taken by pipeline to shore for separation. The ratio of water to oil in the produced fluid can vary by several orders of magnitude but usually increases with time. If there are any significant quantities of sand in the produced fluid, well completion techniques or well flow rates are modified to reduce sand volumes.

There are three methods of handling produced water:

(i) the produced water can be treated and re-injected into the reservoir together with water flood water;

(ii) the produced water may be separated and treated on the platform then discharged over the side; or

(iii) the oil and water stream can be transported to shore for treatment and discharge.

The methods used in the five existing offshore areas reviewed are set out on Table 4-1.

Oil can be separated from sand and water by the following treatment processes (Brown & Root 1974):

(i) Skim piles: large diameter pipes containing internal baffled sections and an outlet at the bottom. They are intermittent flow devices. During the period of no flow, oil will rise to the quiescent areas

TABLE 4-1

EXISTING OFFSHORE TREATMENT TECHNOLOGIES PRODUCED WATER AND SAND

OFFSHORE AREA	TREATMENT TECHNOLOGY
Gulf of Mexico	Gravity separation of insoluble oil in a skim tank (or gun barrel) followed by flotation to meet a standard of 72 mg/L (max.). Equipment located on offshore platform and treated water is discharged into the adjacent waters. For nearshore areas, the produced water is moved by pipeline to shore for treatment and disposal.
California	Pipeline to shore for disposal by injection.
Cook Inlet	Pipeline to shore for treatment by gravity separation of insoluble oil in a skim tank and flotation unit followed by discharge into Cook Inlet. Sand that is removed is collected and taken to shore for disposal.
North Sea - United Kingdom	Gravity Separation of insoluble oil by corrugated plate interceptors or gas flotation to meet a standard of 40 mg/L followed by discharge into the adjacent waters. Cyclone desander used to remove sand from produced water. Oily sand cleaned in wash cyclones with or without detergent.
North Sea - Norway	Gravity separation followed by discharge through a sea sump to meet a standard of 25 mg/L for large production platforms and 30 mg/L for small platforms. In the case of Statfjord, the produced water is also treated in a flotation unit.

below the underside of the inclined baffle plates where it coalesces (see Figure 4-1). Due to the difference in specific gravity, oil is forced upward through oil risers from baffle to baffle. Oil is collected above the flowing stream and removed by either a submerged blowcase or pump. These devices operate intermittently and will move the separated liquid to a skimming vessel for further treatment (Engineering Specialties Inc. 1981). Factors that affect the operation of most gravity separation devices would also affect operation of the skim pile.

(ii) Earthen pits: used for oil/water separation only when the produced fluid is taken to shore for treatment. They are used when high retention time can be provided and thus when space is not limited. (see Figure 4-2).

(iii) Tanks: used primarily to provide surge volume and primary separation of oil and water before treatment in a higher performance system such as the processes described below (Figure 4-3).

(iv) Flotation units: gas under pressure is dissolved in the water/oil mixture which is subsequently de-pressured resulting in the release of minute gas bubbles. The gas bubbles float oil to the surface where it is separated by being skimmed off the surface. Dispersed (induced) gas flotation operates according to the same principles with the difference being that gas bubbles are induced by mechanical means (see Figures 4-4 and 4-5).

(v) Plate coalescers (corrugated plate interceptors (CPI), tilted plate interceptor (TPI): closely spaced parallel plates are used to improve efficiency of the gravity separation process. These units can be upset by rapid changes in flow rates and by a build-up of sand and scale on the plates. This build-up must be removed periodically to maintain separation efficiency (see Figure 4-6).

(vi) Fibrous media coalescers: a fixed filter element made of fibreglass or other materials is used to encourage oil coalescence of droplets and allow oil to be removed by gravity separation. The fixed elements are generally

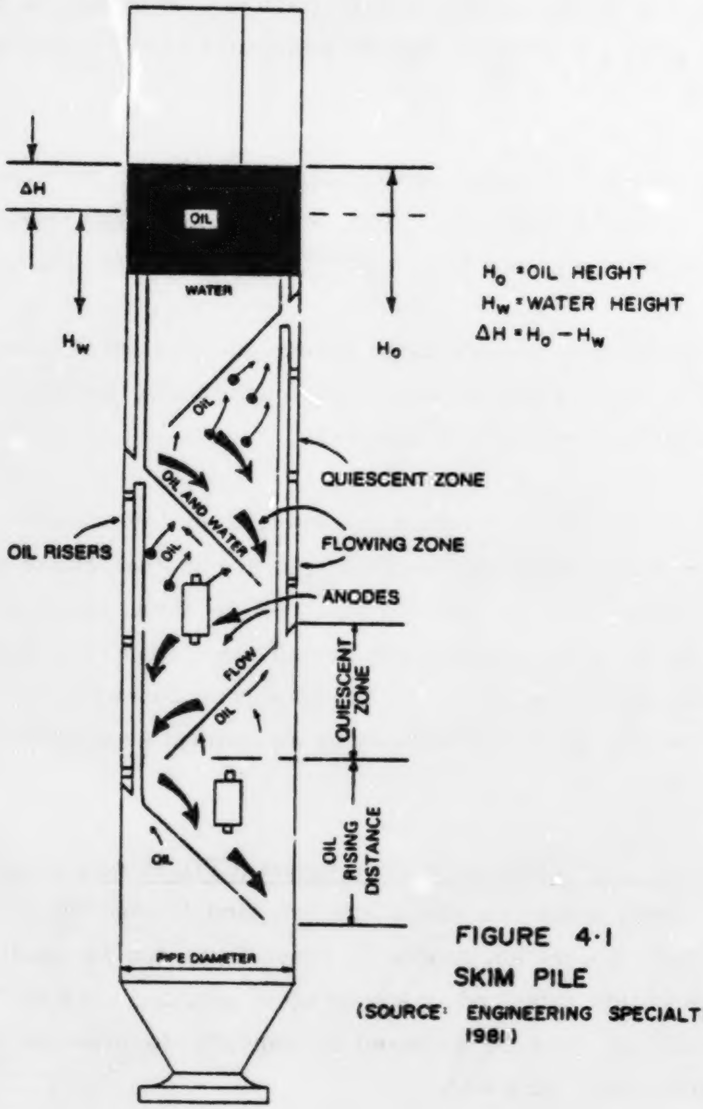
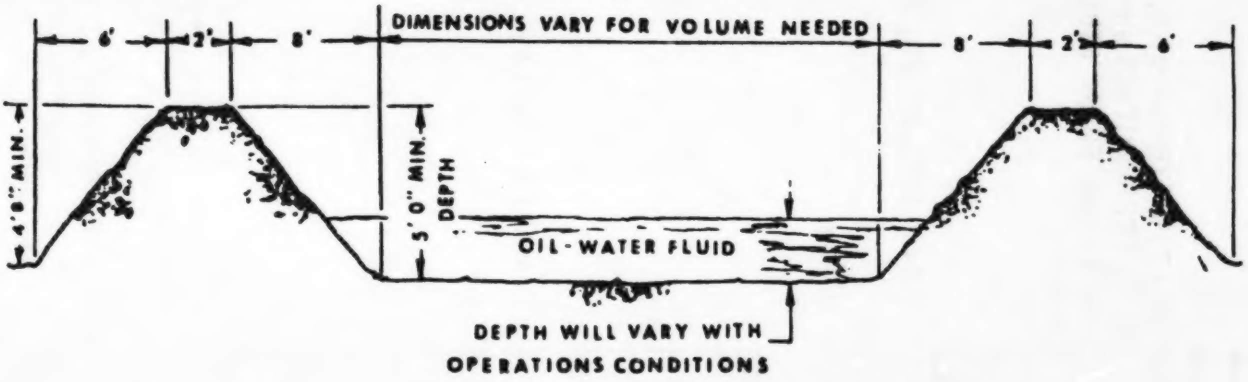

ΔH
OIL
WATER
H_W
H_O
H_o = OIL HEIGHT
H_W = WATER HEIGHT
$\Delta H = H_o - H_W$
OIL
OIL AND WATER
QUIESCENT ZONE
OIL RISERS
OIL
FLOWING ZONE
ANODES
FLOW
QUIESCENT ZONE
OIL
OIL RISING DISTANCE
OIL
PIPE DIAMETER

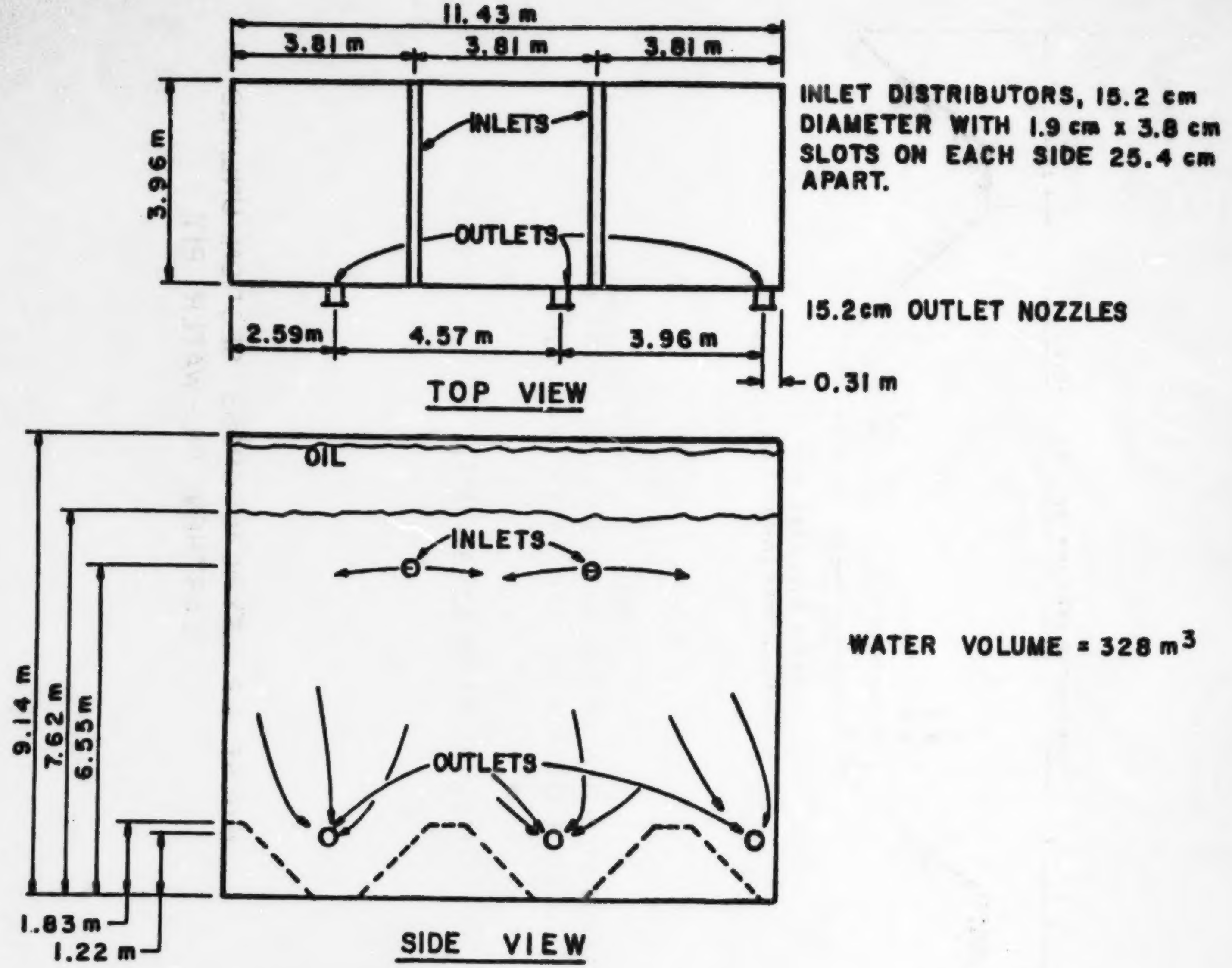
FIGURE 4·1
SKIM PILE
(SOURCE: ENGINEERING SPECIALTIES INC. 1981)


6'
2'
8'
DIMENSIONS VARY FOR VOLUME NEEDED
8'
2'
6'
4'8" MIN.
5'0" MIN. DEPTH
OIL-WATER FLUID
DEPTH WILL VARY WITH OPERATIONS CONDITIONS

NOTE
PITS ARE EQUIPPED WITH PIPE DRAINS FOR SKIMMING OPERATIONS TO OBTAIN OIL-FREE WATER DRAINAGE

(SOURCE: TRAIN ET AL. 1976)

FIGURE 4·2 TYPICAL CROSS SECTION UNLINED EARTHEN OIL-WATER PIT


11.43 m
3.81 m
3.81 m
3.81 m
3.96 m
INLETS
OUTLETS
2.59m
4.57 m
3.96 m
0.31 m
TOP VIEW
9.14 m
7.62 m
6.55 m
1.83 m
1.22 m
OIL
INLETS
OUTLETS
SIDE VIEW

INLET DISTRIBUTORS, 15.2 cm DIAMETER WITH 1.9 cm x 3.8 cm SLOTS ON EACH SIDE 25.4 cm APART.

15.2cm OUTLET NOZZLES

WATER VOLUME = 328 m^3

FIGURE 4·3 SKIM TANK SKETCH (SOURCE: JACKSON ET AL. 1981)

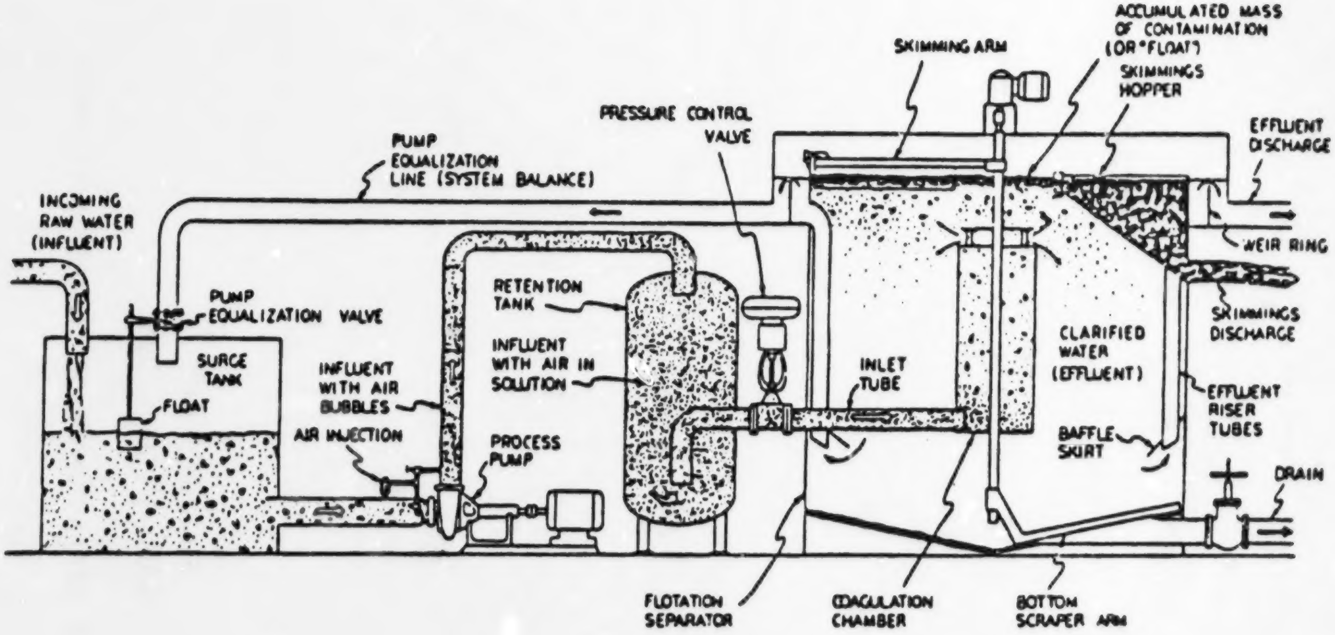
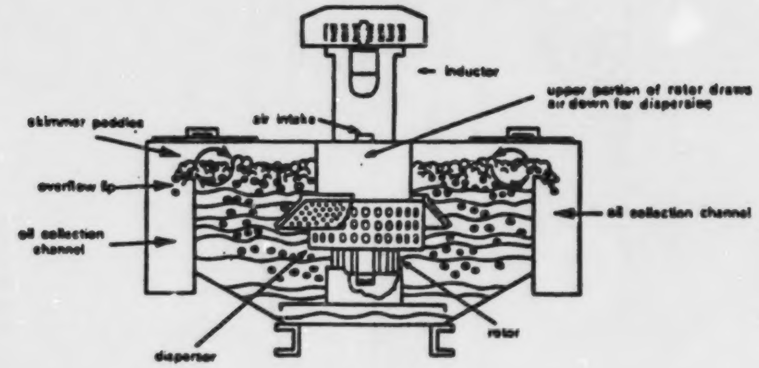

INCOMING RAW WATER (INFLUENT)
PUMP EQUALIZATION LINE (SYSTEM BALANCE)
PRESSURE CONTROL VALVE
SKIMMING ARM
ACCUMULATED MASS OF CONTAMINATION (OR "FLOAT")
SKIMMINGS HOPPER
EFFLUENT DISCHARGE
WEIR RING
PUMP EQUALIZATION VALVE
SURGE TANK
FLOAT
RETENTION TANK
INFLUENT WITH AIR BUBBLES
INFLUENT WITH AIR IN SOLUTION
AIR INJECTION
PROCESS PUMP
INLET TUBE
CLARIFIED WATER (EFFLUENT)
SKIMMINGS DISCHARGE
EFFLUENT RISER TUBES
BAFFLE SKIRT
DRAIN
FLOTATION SEPARATOR
COAGULATION CHAMBER
BOTTOM SCRAPER ARM

FIGURE 4·4

FULL FLOW PRESSURIZATION
DISSOLVED AIR FLOTATION

(SOURCE: INSTITUTE OF OFFSHORE
ENGINEERING, 1976)

a. Transverse section of a gas flotation unit


inductor
upper portion of rotor draws air down for dispersion
skimmer paddles
air intake
overflow lip
oil collection channel
oil collection channel
rotor
disperser

b. Longitudinal section of a four-unit system

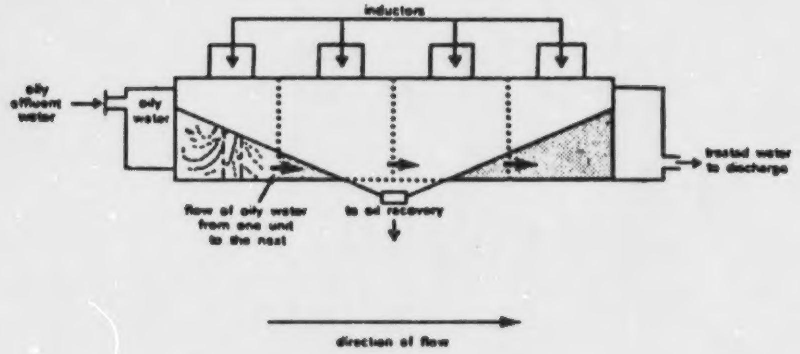
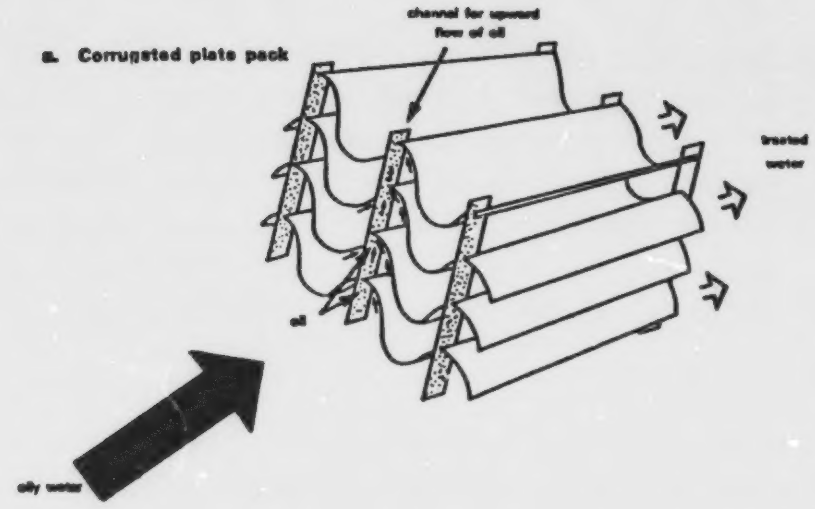

inductors
oily effluent water
oily water
treated water to discharge
flow of oily water from one unit to the next
to oil recovery
direction of flow

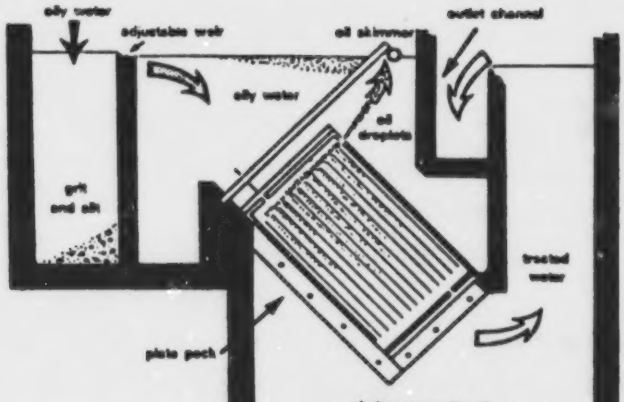
FIGURE 4·5
GAS FLOTATION

(SOURCE: U.K. DEPARTMENT OF ENVIRONMENT, 1976)



a. Corrugated plate pack

channel for upward flow of oil
treated water
oil
oily water



b. Unit in sump

oily water
adjustable weir
oil skimmer
outlet channel
oily water
oil droplets
grit and silt
treated water
plate pack
sludge compartment

FIGURE 4·6
CORRUGATED PLATE INTERCEPTOR

(SOURCE: U.K. DEPARTMENT OF ENVIRONMENT. 1976) efficient for coalescing the oil and removing any fine suspended solids. The build-up of solids on the fibres, however, causes a deterioration in performance, thus necessitating frequent filter element replacement (see Figure 4-7).

(vii) Loose media coalescers: multi-grade sand or other loose filtration media are used to remove suspended solids and cause oil droplets to coalesce. These units are backwashed periodically to remove the oil and suspended solids that collect on the filtration media. The backwash is collected in tanks where the bulk of the oil or solids is separated by gravity and the decanted backwash water returned upstream of the loose media coalescers (see Figure 4-8).

Most of the above methods use gravity to separate oil drops from water. The gravity separation of oil drops from water is described by Stoke's law:

$$v = \frac{g}{18m} (P_w - P_o)\ D^2$$

where:

v = the rate of rise or fall of the drop or particle (m/s)
m = the water viscosity (kg/m-s)
P_w = the water density (kg/m^3)
P_o = the oil density (kg/m^3)
D = diameter of the drop (m)
g = gravitational constant. (m/s^2)

This separation principle is used directly in pits and tanks. In skim piles and plate coalescers, gravity separation is assisted by oil droplet coalescence. Attachment of fine gas bubbles to a drop of oil in a flotation system decreases the effective density of the drop which then separates from the water according to Stoke's Law.

Fibrous or loose media coalescers are based on the principle of impact of the drops on a surface that is wetted by the drop followed by drop coalescence and separation by gravity.

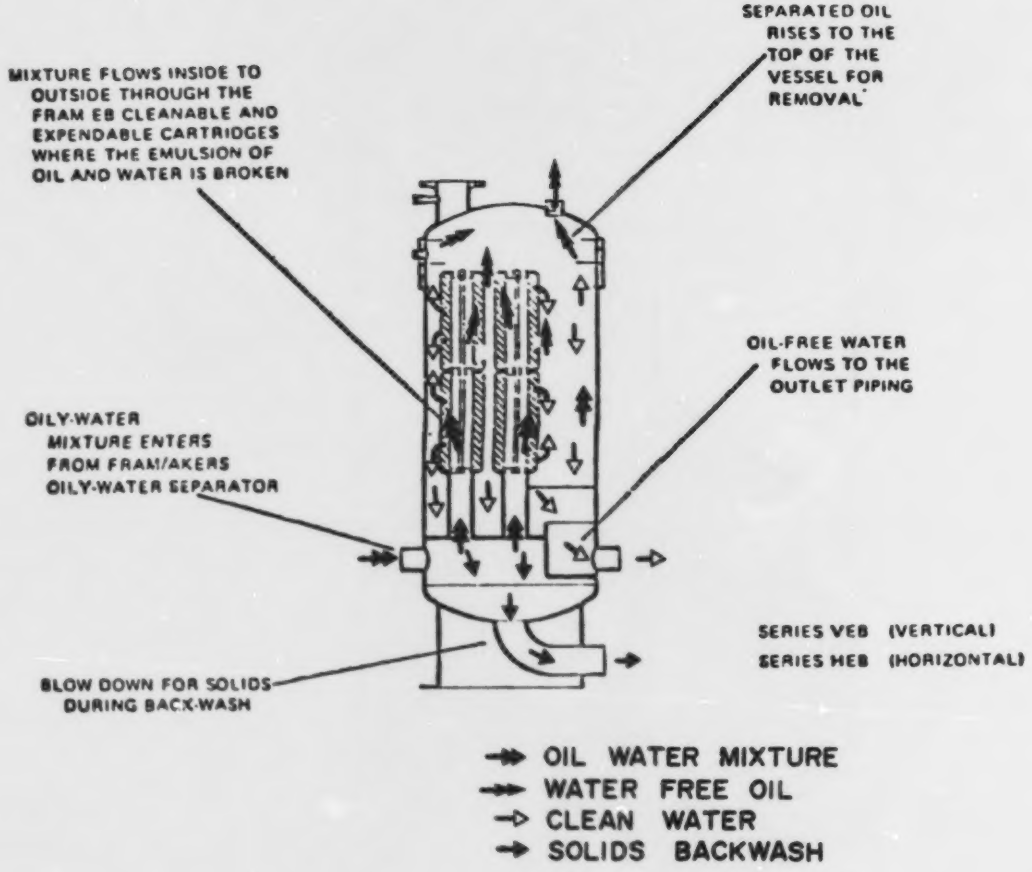

SEPARATED OIL RISES TO THE TOP OF THE VESSEL FOR REMOVAL
MIXTURE FLOWS INSIDE TO OUTSIDE THROUGH THE FRAM EB CLEANABLE AND EXPENDABLE CARTRIDGES WHERE THE EMULSION OF OIL AND WATER IS BROKEN
OIL-FREE WATER FLOWS TO THE OUTLET PIPING
OILY-WATER MIXTURE ENTERS FROM FRAM/AKERS OILY-WATER SEPARATOR
SERIES VEB (VERTICAL)
SERIES HEB (HORIZONTAL)
BLOW DOWN FOR SOLIDS DURING BACK-WASH
OIL WATER MIXTURE
WATER FREE OIL
CLEAN WATER
SOLIDS BACKWASH

FIGURE 4-7

FIBROUS MEDIA COALESCER

(SOURCE: FORSTER ET AL. 1973)

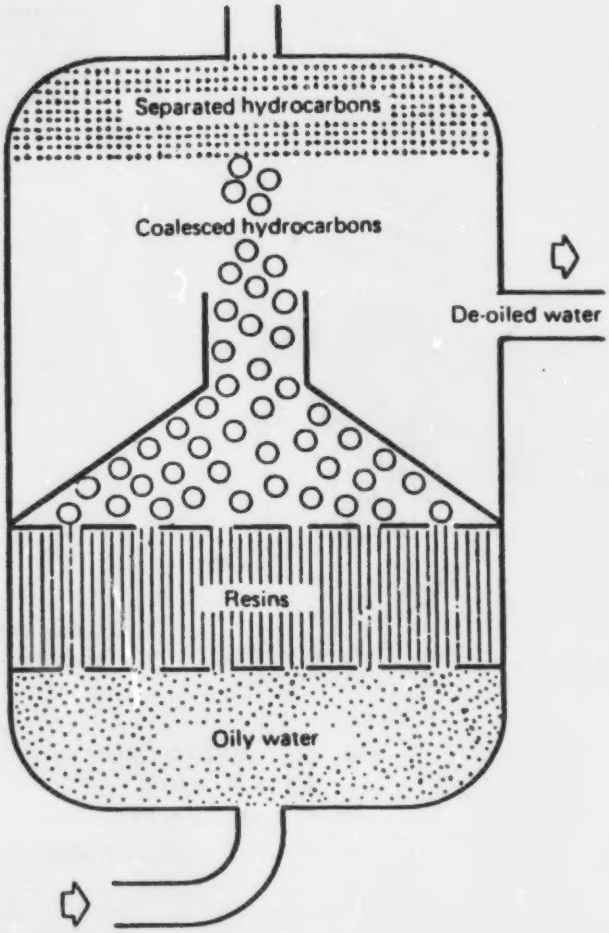

Separated hydrocarbons
Coalesced hydrocarbons
De-oiled water
Resins
Oily water

FIGURE 4·8
GRANULAR MEDIA COALESCER
(SOURCE: TRAMIER, 1982a)

Oil is present in water in the form of a continuum from molecular size through to droplet size. Thus, reducing the oil content of produced water involves removing three basic forms of oil: large droplets of coalescable oil, small droplets of emulsified oil and dissolved compounds.

Stoke's Law is generally applied to gravity separator design for removal of all droplets above a certain diameter. Generally the design basis selected is:

Skim tanks	- all droplets above 150 μm
Proprietary separators	- all droplets above 60 μm
CPI Units	- all droplets above 30-40 μm
Flotation	- all droplets above 10-20 μm

Thus the level of dispersed oil after treatment is directly dependent on the oil drop size distribution upstream of the treatment equipment. It has also been shown that flotation and other gravity separation equipment is not effective in removing oil droplets smaller than 10 microns (Jackson et al. 1981).

Performance of the various separation methods has been measured (Brown & Root 1974) and the results are detailed in Table 4-2. Figures 4-9 to 4-11 show probability distributions of effluent oil data for flotation systems, loose media coalescers and mixed-media coalescers. The data exclude upset and bypass conditions.

Oil droplet formation is promoted by shear forces encountered in pumps, chokes, valves and high flow rate pipelines. These droplets are stabilized by surface active agents, fine solids, and high static charge on the droplet (Ferraro and Fruh 1977). Any operational change that promotes the formation of smaller droplets or the stabilization of small droplets will result in upset conditions and higher contents of suspended oil after treatment. Upset conditions can be caused by detergent washdowns in deck drainage entering the treatment unit, unusually high flow volumes caused by heavy rain fall, and equipment failures. Other factors leading to treatment plant upsets are slugs of completion and workover fluids passing through with the produced water. Similar upset conditions can occur at shore treatment facilities when slugs of chemicals pass down the pipeline for the production platform. This has been observed at North Sea facilities (pers. comm. Johnston).

Likewise, some of the chemicals added (such as hydrate inhibitor, scale inhibitor, biocide, emulsion breaking chemical, or corrosion inhibitor) can end up in the produced water and can be analyzed as "oil and grease". In this event, an increase in chemical addition due to operational changes, may be interpreted as higher oil content.

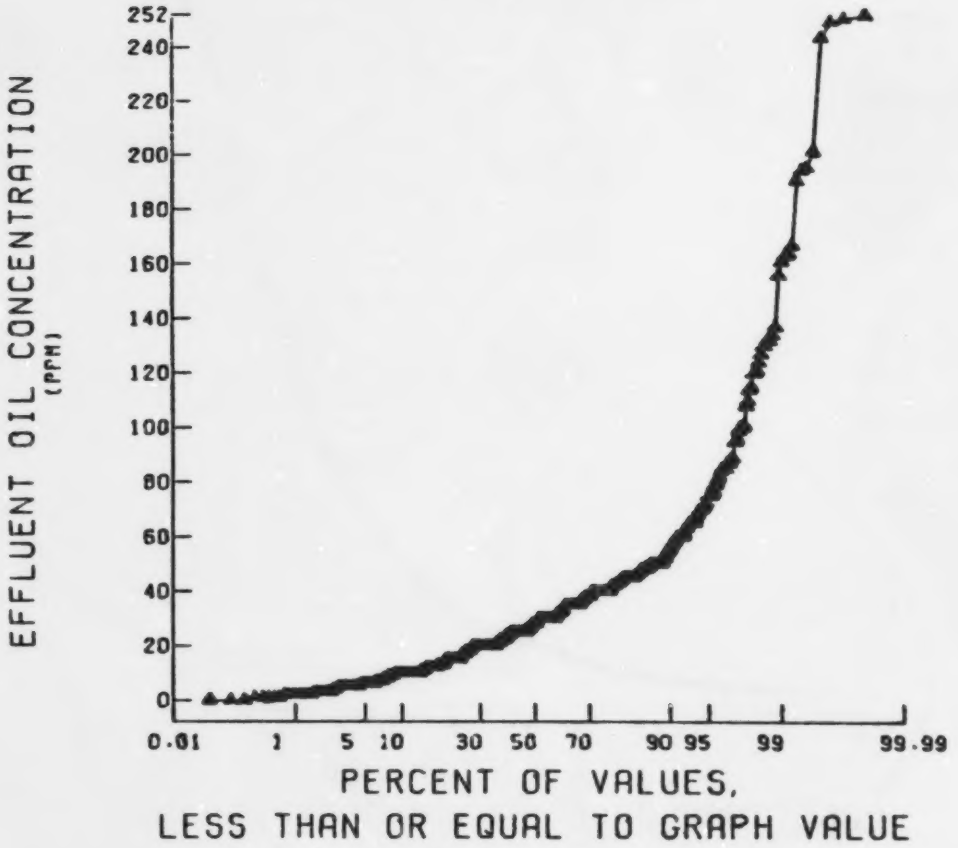
TABLE 4-2

SUMMARY OF VARIABILITY OF EFFLUENT OIL CONCENTRATIONS FOR DIFFERENT TREATMENT PROCESSES

PROCESS TYPE	AVERAGE OF MEAN EFFLUENT OIL CONCENTRATION (mg/L)	MEAN EFFLUENT OIL CONCENTRATION ACHIEVED BY 75% OF UNITS ANALYZED (mg/L)	EFFLUENT OIL CONCENTRATION VALUES WHICH ARE NOT EXCEEDED SPECIFIED PERCENT OF THE TIME (mg/L)			
			50%	90%	95%	98%
PITS	35.4	43	25	75	100	140
TANKS	41.9	52	30	90	110	155
FLOTATION SYSTEMS	33.5	44	25	50	70	100
PLATE COALESCERS	56.8	78	35	100	130	200
FIBROUS MEDIA COALESCERS	42.0	55	20	70	110	180
LOOSE MEDIA COALESCERS	21.8	24	15	40	50	60

Adapted from tables in Brown and Root (1974).

FIGURE 4·9
PROBABILITY DISTRIBUTION OF EFFLUENT OIL DATA FOR FLOTATION SYSTEMS



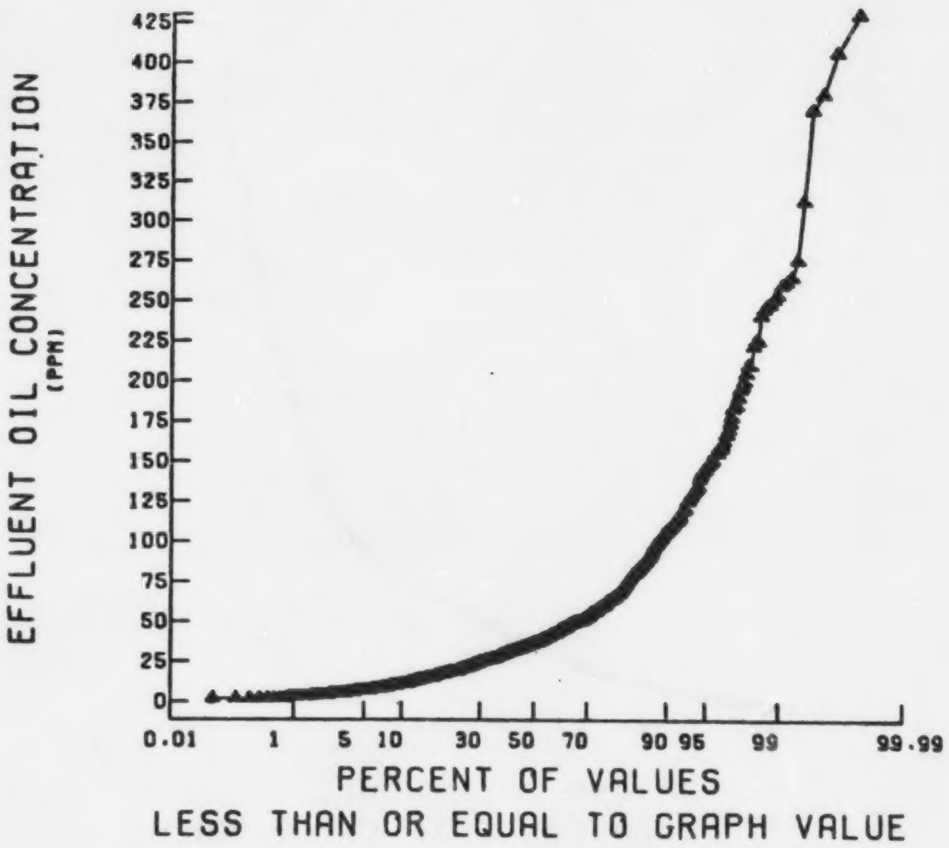
UNIT TYPE: FLOTATION

NUMBER OF SAMPLES: 1218

MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIABILITY
3.28E 1	2.71E 1	8.25E-1

(SOURCE: BROWN AND ROOT INC., 1974)

FIGURE 4·10
PROBABILITY DISTRIBUTION OF EFFLUENT OIL DATA FOR PLATE COALESCERS



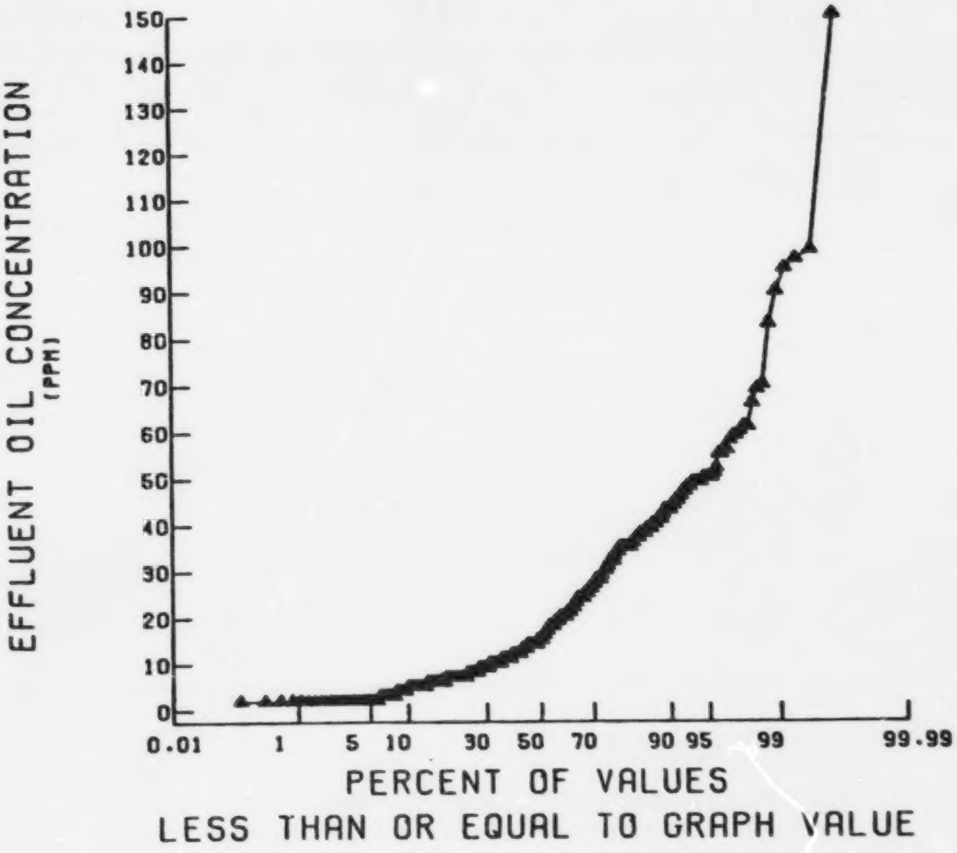
UNIT TYPE: PLATE COALESCERS

NUMBER OF SAMPLES: 995

MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIABILITY
5.02E 1	4.93E 1	9.82E-1

(SOURCE: BROWN AND ROOT INC., 1974)

FIGURE 4·11
PROBABILITY DISTRIBUTION OF EFFLUENT OIL DATA FOR LOOSE MEDIA COALESCERS



UNIT TYPE: LOOSE MEDIA COALESCERS

NUMBER OF SAMPLES: 467

MEAN	STANDARD DEVIATION	COEFFICIENT OF VARIABILITY
2.10E 1	1.77E 1	8.41E-1

(SOURCE: BROWN AND ROOT INC., 1974)

TABLE 4-3

EFFECT OF UPSET CONDITIONS ON OIL CONTENT OF PRODUCED WATER EFFLUENT

PLATFORM	AVERAGE OIL (mg/L)		NORMAL MAXIMUM OIL (mg/L)		UPSET CONDITIONS OIL (mg/L)	
	IR	GR	IR	GR	IR	GR
SS107	15	8	29	31	*	*
SS198G	36	18	53	45	*	*
BDCCF5	36	26	52	45	*	*
ST131	37	12	57	43	76-92	50-57
BM 2C	39	22	50	52	*	*
SM130B	48	48	86	98	*	*
E118CF	46	52	-	-	102-155	78-88
WD45C	81	63	72	56	165-516	152-465
ST177	95	64	114	81	135-542	141-373
SP65B	106	77	84	85	270-448	183-390

Source: Adapted from Jackson et al. 1981

Notes: (1) IR - mg/L oil measured by EPA Infrared Method
GR - mg/L oil measured by EPA Gravimetric Method

(2) All platforms had air flotation treatment systems and were sampled over a 10-day period.

(3) Upset defined by sharp increase in influent oil due to a variety of factors discussed in the text.

(*) No upset conditions recorded over 10-day sample period.

Produced water in contact with oil in the formation over geologic time contains dissolved compounds such as soluble oil (10-60 mg/L) and polar compounds (Jackson et al. 1981). Many of these soluble components of crude oil (low molecular-weight aromatics, high branched aliphatics and polar organics) will show up in the analysis as "oil and grease". A change in the amount produced from different wells flowing to a platform could also result in a change in dissolved oil content and be interpreted as an "upset" of treatment equipment.

An example of the effect of these upset conditions on "oil and grease" content of produced water in the Gulf of Mexico is set out on Table 4-3. Figures 4-12 and 4-13 show the variation in oil content with time for two flotation unit effluents, one which experienced frequent upsets and one which did not.

Table 4-4 below shows the variable performance of nine identical gravity separators handling different oils and different flow rates.

TABLE 4-4

PERFORMANCE OF DIFFERENT GRAVITY SEPARATORS

UNIT	WATER TEMP. °C	OIL sp. gr.	FLOW-RATE m^3/h	OIL CONTENT AT THE OUTLET (mg/l)
A	97	0.911	122	195
B	89	0.963	70	564
C	85	0.911	51	42
D	99	0.849	150	250
E	38	0.885	69	696
F	93	0.917	58	205
G	86	0.884	74	279
H	95	0.833	178	17
I	92	0.831	15	14

Source: Adapted from Tramier 1982.

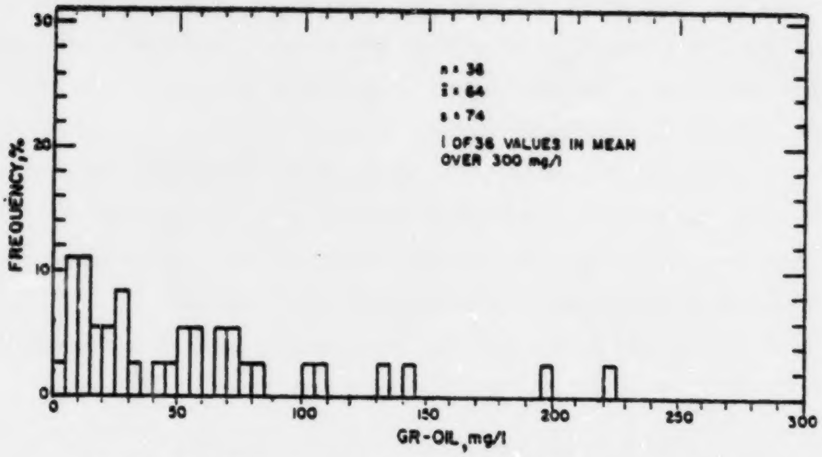


Figure 4-12a ST177 flotation unit effluent, GR-oil histogram.
(Source: Jackson *et al.*, 1981)

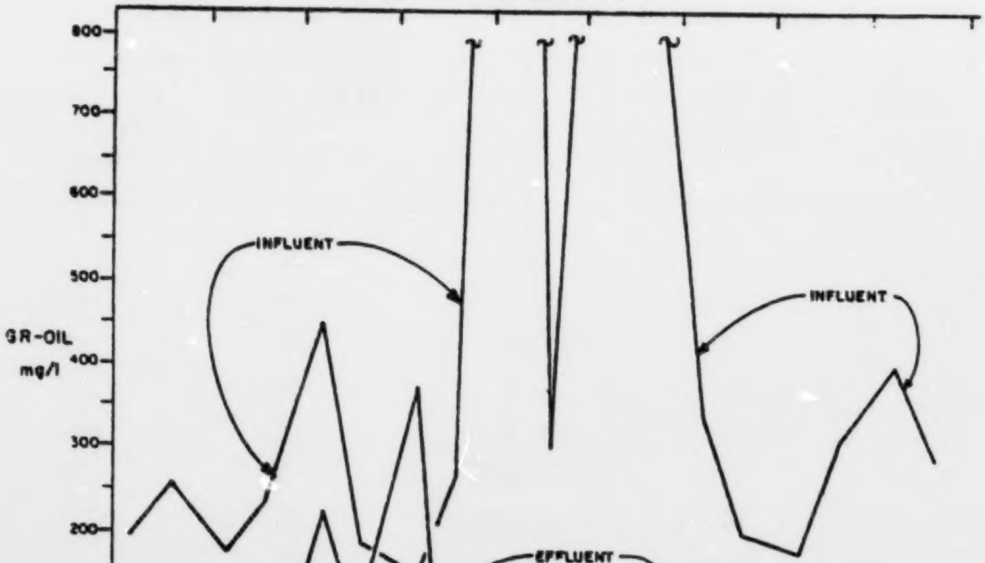


Figure 4-12b ST177 flotation unit performance, GR-oil vs time.
(Source: Jackson *et al.*, 1981)

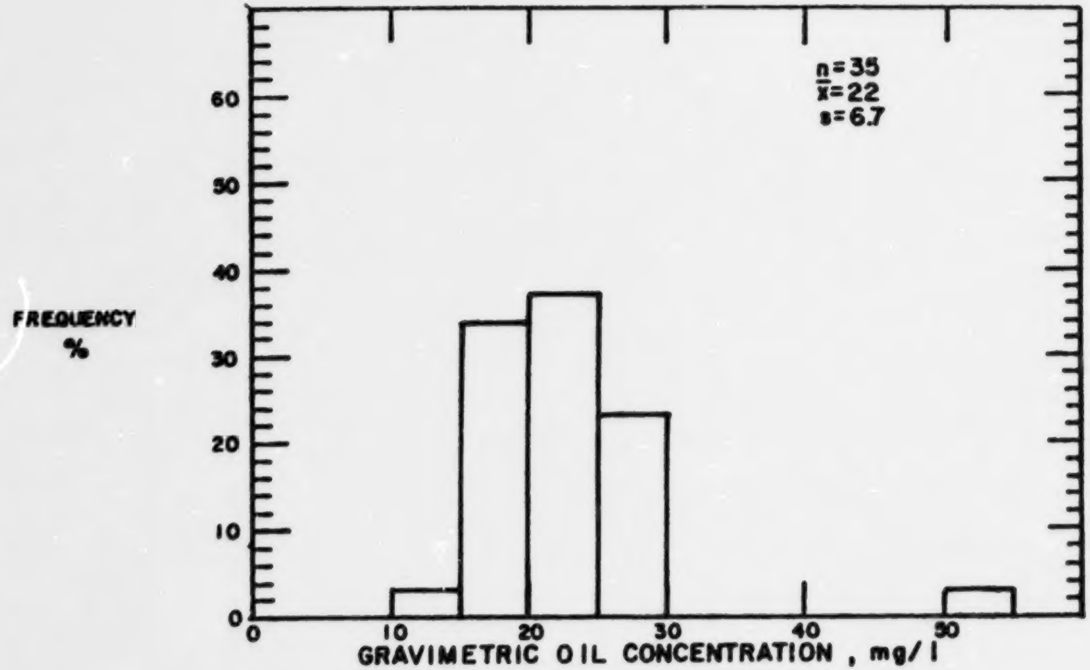


Figure 4-13a BM2C flotation unit effluent, GR-oil histogram.
(Source: Jackson et al., 1981)

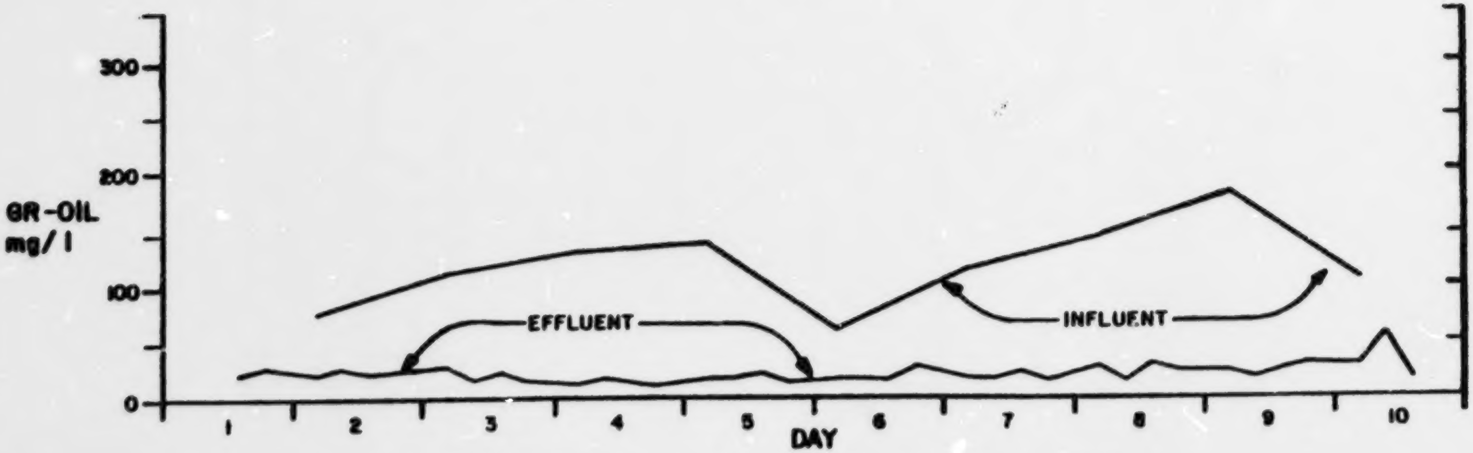


Figure 4-13b BM2C flotation unit performance, GR-oil vs time.
(Source: Jackson et al., 1981)

The performance of a treatment unit can vary even on the same day. For instance with a gas flotation unit, the following results have been reported (Tramier 1982):

Time	**0600**	**0745**	**1000**	**1200**	**1400**	**1630**
Oil content at outlet (mg/L)	33	51	20	31	33	120

While there is no specific information available on equipment bypass, the operating cost factors (developed by Brown & Root 1975) show that the cost of operating and maintaining water treatment equipment is higher than for mechanical equipment:

Equipment	**Operating Cost Factor % of Capital Investment**
Tanks	11
Flotation	11
Plate Coalescers	33
Filters	8
Desanders	9
Pumps & Drivers	3

Directionally this means that water treatment equipment will be attended because of upsets and bypassed for maintenance more frequently than mechanical equipment, which is generally considered to require the most frequent shutdowns for repair.

Using data from Brown & Root (1974) and (1975), the cost of treatment of produced water for the five principal methods is as follows:

COST OF PRODUCED WATER TREATMENT
($/m ^{3} Produced Water)

Method	Design Produced Water Flow Rate 300 m^3/d	3,000 m^3/d	8,000 m^3/d
Pit (onshore)	$ 0.20	$ 0.05	$ 0.03
Tank	0.82	0.45	0.43
Flotation	0.85	0.28	0.18
Plate Coalescer	0.44	0.10	0.05
Loose Media Coalescer	1.10	0.40	0.30

These costs are in constant Canadian dollars, first quarter of 1983 and include operating cost plus financial costs amounting to 25% of installed equipment cost (including incremental platform cost and power generation facility cost).

1.1.2 Ballast and Storage Displacement Water

Oil produced offshore is delivered to market by pipeline to shore or by offshore tanker loading. Some oil storage is required for each, resulting in ballast water or storage displacement water. The treatment methods used in five existing offshore areas is given in Table 4-5. The possibility of oil contamination of ballast water should be small, because most tankers will conform to IMCO regulations which require segregated ballast in new crude oil tankers of 20,000 DWT and over; and in existing crude oil tankers of 40,000 DWT and over (Isaacson 1979). During special circumstances, such as very rough seas when the tanker is empty, ballast water may be introduced into oil tanks. This water will be contaminated with oil and may require treatment.

The two main types of offshore oil storage are floating and underwater. Storage tankers are usually equipped with oil storage tanks, slop tanks, ballast water tanks and a pumping system. They are not normally modified to collect dirty ballast from loading tankers. Floating storage may be provided either by a permanently moored tanker or by a mooring point with integral storage (SPAR System) whereas underwater storage is provided as part of the platform support structure.

TABLE 4-5

EXISTING OFFSHORE TREATMENT TECHNOLOGIES BALLAST AND STORAGE DISPLACEMENT WATER

OFFSHORE AREA	TREATMENT TECHNOLOGY
Gulf of Mexico	No ballast or displacement water is handled offshore. All crude oil piped to shore for land distribution.
California	No ballast or displacement water is handled except segregated ballast for the Santa Ynez floating production unit (platform ballast).
Cook Inlet	No ballast or displacement water is handled except at the Port of Valdez. There, the ballast water is treated in settling tanks, flotation units and settling ponds to meet a discharge limit of 10 mg/L oil maximum.
North Sea - United Kingdom	Water is treated in settling tanks followed by gravity separators (CPI) for removal of insoluble oil and then discharged to the sea. Most offshore loading facilities use dedicated tankers with segregated ballast. Most offshore fields have no offshore loading, but transport oil by pipeline to shore terminals for processing. Attendant ballast handling facilities are also on shore and use some combination of plate separator, flotation unit, sand filter, biological oxidation unit, and retention pond.
North Sea - Norway	Displaced sea water is treated for removal of insoluble oil in a TPI, then mixed with produced water and discharged to the sea. Ballast water is treated for emulsions and then mixed with the displaced sea water.

The SPAR System operates as a floating storage unit and tanker loading terminal. Processed crude oil is pumped continuously to the SPAR from the adjacent production platform through submarine pipelines. The crude flows into the storage tanks at the top, displacing sea-water from the bottom. The displaced water passes upwards through a riser into an oil/water separator tank, from which it is pumped by submersible pumps through a filter to the sea. To keep the SPAR at constant draught, the storage tanks, when not filled with crude oil, are balanced with sea water (Tramier et al. 1982b).

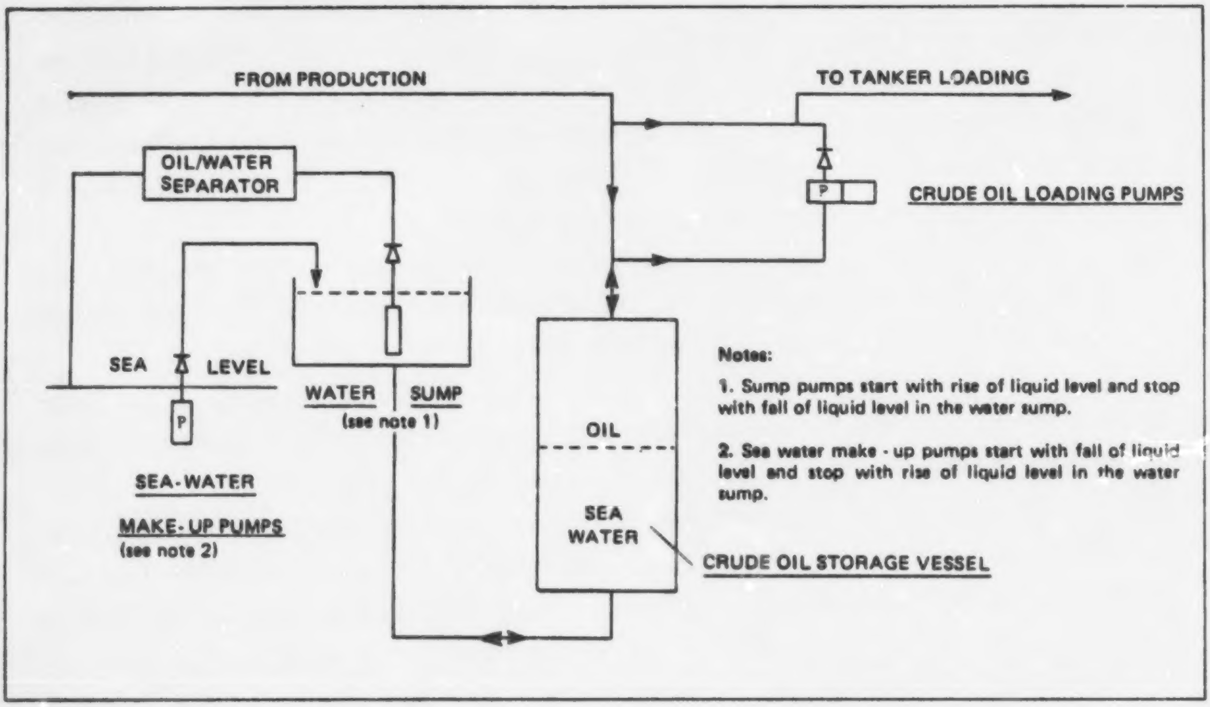
Underwater storage systems have been used in the North Sea in conjunction with steel or concrete platforms. Referring to Figure 4-14, oil is injected into the storage tank where it displaces water to the sump tank in which the water level is kept constant by an overflow system. Excess water is discharged to an oil separator and then to the sea (Tramier et al. 1982b). Most North Sea production fields now transport oil by pipeline to loading terminals on shore.

The above comments apply particularly to the United Kingdom and Norwegian North Sea because in the Gulf of Mexico, California offshore and Alaskan offshore areas, oil is carried by pipeline to shore in virtually every instance.

Displacement water is usually not significantly contaminated by oil and could be discharged to the sea without treatment. Nevertheless, it is normally treated to an acceptable oil content by a plate interceptor (Tramier 1982).

Ballast water treatment onshore consists of gravity settling in a storage tank followed by air flotation and polishing ponds. This system is used at Valdez (Alaskan crude oil terminal) and at Flotta (North Sea oil from Piper, Claymore and Tartan fields). Recent modification to the Flotta treatment system has allowed the segregation of the more easily treated ballast water from pipeline and desalter oily waters; the latter had previously been responsible for treatment plant upsets (pers. comm. Johnston). In the case of the Teeside terminal (Ekofisk field) the ballast water treatment consists of gravity settling in storage tanks followed by dissolved air flotation and mixed media deep bed filtration.

The expected performance of ballast water treatment systems is set out in Tables 4-6 and 4-7.


FROM PRODUCTION
TO TANKER LOADING
OIL/WATER SEPARATOR
P
CRUDE OIL LOADING PUMPS
SEA LEVEL
WATER SUMP
(see note 1)
P
SEA-WATER
MAKE-UP PUMPS
(see note 2)
OIL
SEA WATER
CRUDE OIL STORAGE VESSEL

Notes:

1. Sump pumps start with rise of liquid level and stop with fall of liquid level in the water sump.

2. Sea water make - up pumps start with fall of liquid level and stop with rise of liquid level in the water sump.

FIGURE 4·14
UNDERWATER CRUDE OIL STORAGE: VARIABLE BED SYSTEM (ENCLOSED TYPE)

(SOURCE: TRAMIER ET AL. 1982)

TABLE 4-6

TYPICAL PERFORMANCE - BALLAST TREATMENT SYSTEMS

SYSTEM	OIL CONTENT IN EFFLUENT (mg/L)		
	U.S. GUIDELINE DATA (4)	LITERATURE SEARCH	MINIMUM RESIDENCE TIME
Tanks	20-100	40-50	min. 10 h
API Separators	20-100	50-100	30 min.
Plate Coalescers - Parallel	20-100	50	5-15 min.
- Corrugated	-	25-30	30 min.
Flotation Systems (1)	5-20	- chemical 15-25	5 min.
		- chemical 5-10	
Sedimentation Clarifiers (1)	5-35	-	-
Filters (1) (2)	3-20	-	-
Biological Treatment (3)	-	1	1-20 h

(1) pretreated with gravity system to below 300 mg/L and if possible below 100 mg/L.

(2) problem of washing filter and waste removal.

(3) not sufficient technology commercially available and very expensive.

(4) U.S. Tech. Information Service Publ. PB-23 612.

(adapted from a table by Johnston and Halliwell 1976)

TABLE 4-7

PERFORMANCE OF BALLAST WATER TREATMENT SYSTEMS

	EFFLUENT OIL (mg/L)			
	VALDEZ	FLOTTA	TEESIDE	SIDI KERIR
Tanks	4.7	30-40	50-100	
Coalescers	-	-	-	4 max.
Flotation Systems	1.9	13-30	-	-
Filters	-	-	-	-
Polishing Ponds	1.9	10-25	-	-

The factors affecting performance are as follows (Tramier, 1982):

Water Characteristics:

Salt Content:	usually a high salt content facilitates the separation and some processes do not work with a low salt content; however some do not work with a high one; the source of the ballast water determines salt content (see Section 3.3, Chapter 2).
Solid Content:	the presence of solid particles in the water usually precludes the use of fibrous bed separation techniques; tank cleaning leads to high solids (silt, iron oxide).
Chemical Content:	chemicals used in oil production (e.g., biocide, corrosion inhibitor) will lower the size of oil droplets, creating separation problems. Oleophilic systems are usually inefficient.
Oil Content:	according to the oil content a one-step or a two-step process is recommended; methods of ballasting and deballasting, condition of passage and previous cargo influence oil content and nature of oil in ballast water.
Temperature:	a high temperature increases the separation but also increases the solubility of oil compounds in water.

Oil Characteristics:

Oil Density:	the lighter the oil, the easier the separation.
Oil Viscosity and Wax Content:	the presence of wax or a high-viscosity oil interferes with filtering or coalescing beds, plates.
Oil Droplet Size:	the larger the droplet size, the easier the separation.

1.1.3 Deck Drainage

Deck drainage includes all water resulting from platform washings, deck washings, tank cleaning operations and run-off from curbs, gutters and drains, including drip pans and work areas (Federal Register 1982).

In the United Kingdom sector of the North Sea, water from open and closed drains on the platform are segregated from produced oily water and discharged to the sea through a skim pile (Moore 1980). During the early life of North Sea fields, while produced water flow is low, deck drainage containing up to 100 mg/L oil is discharged through a skim pile or a sump (pers. comm. Johnston). In the Norwegian North Sea, drainage water is directed to a special gravity separation tank and from there to the produced water skim pile (Schreiner 1980).

The current practice in the Gulf of Mexico varies. Some companies discharge drain systems through a skim pile to meet the "no discharge of free oil" requirement while others take all drains into a sump tank located below the main deck. Oil is separated by gravity and pumped to the oil treating system while water is discharged to the sea directly or through a skim pile.

In Cook Inlet, crank case oil is collected separately and oil-base mud is kept out of platform drain systems. Deck drainage is treated by gas flotation to an average of 25 mg/L oil or in gravity separators before discharge.

Some California platforms mix deck drainage water with produced water which is piped to shore for treatment and disposal (Train et al. 1976). On other platforms, drainage is mixed with produced water, filtered and reinjected (Exxon 1981).

Deck drainage effluent limitations for the Gulf of Mexico were initially established equivalent to those for produced water but subsequently were changed to "no discharge of free oil" (this means no surface sheen or bottom emulsion). The original decision was based on the assumption that deck drainage was mixed with produced water. This mingling is not usually practised because (Berry 1980):

(i) the resulting flow variations would seriously upset the produced water treatment facility;

(ii) deck drainage water, saturated with oxygen, when mixed with produced water can cause formation of solids which foul treatment equipment;

(iii) detergents, used for washing oil off the decks, cause emulsification of oil and serious upsets in produced water treatment facilities.

This rationale was further confirmed during discussions with industry representatives having offshore operating experience.

Skim piles are guaranteed to meet the regulations for Gulf of Mexico and California which is "no discharge of free oil". Sizing of the skim pile is based on a 20-minute residence time. No performance data are available for skim piles.

Skim piles are reported to have been located at 40 m, 61 m, and 74 m (Frigg, Piper and Claymore) water depth, thus having an average length of about 70 m and a diameter of approximately 1 m. Weighing 30 tonnes these units would cost about $120,000.

1.1.4 Gas/Oil Processing Wastes

Very little sour gas is processed in the Gulf of Mexico, offshore California, offshore Alaska and in the United Kingdom and Norwegian North Sea. Thus offshore gas/oil processing produces sulphur-free wastes in most regions. One field in offshore California produces sour gas and has a floating storage and processing facility which includes a sour gas stripper (Exxon 1981). The treatment of wastes in various offshore areas is given in Table 4-8.

Glycol spilled or drained from equipment is collected in a special glycol sump tank and pumped back into the glycol system for re-use. Oil or sludge separated in this tank is dumped into the closed drain system and processed along with deck drainage water.

TABLE 4-8

EXISTING OFFSHORE TREATMENT TECHNOLOGIES GAS/OIL PROCESSING WASTES

OFFSHORE AREA	TREATMENT TECHNOLOGY
Gulf of Mexico	Processing wastes are collected in the same drain system as the closed hydrocarbon drains. This material is collected in a sump tank where oil separates by gravity. The water phase is discharged through a sump pile or skim pile.
California	Mixed with produced water and re-injected.
Cook Inlet	No information.
North Sea - United Kingdom	Direct discharge via sea sump or skim pile in early phase of production; through produced water treatment system during main phase of production.
North Sea - Norway	Effluent from process drains is mixed with produced water in the sea sump which discharges below the surface.

1.2 Drilling Fluids and Cuttings

1.2.1 Water- Base Muds and Cuttings

Drilling fluid serves a number of important functions, but it primarily removes drill cuttings and maintains wellbore integrity. The mud is circulated down the drill pipe, through nozzles in the bit (picking up the drill cuttings) and returns to the surface between the drill pipe and the walls of the drilled hole. At the surface, the cuttings are removed and the mud is re-circulated.

Commercial solids (mud additives) such as barite, bentonite and various thinners, are deliberately added to the mud to achieve certain properties. All commercial solids have a mean diameter less than 2 µm, except barite which ranges in size from less than 2 µm to 74 µm. Drilled solids (cuttings) vary in size from less than 2 µm to more than 25,400 µm in diameter and their composition is the same as the formation (Montgomery 1981).

There are five types of equipment used to remove unwanted solids from drilling fluids (Reef Mud 1981).

Shaleshaker: a vibrating screen through which returning mud is passed for removal of large solids. The standard shaker removes cuttings larger than 440 µm while the fine screen shaker removes cuttings larger than 150 µm.

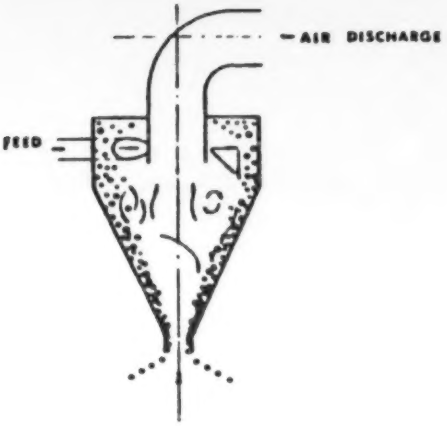
Desander: a cyclone separator which is designed to remove solids larger than 40 to 90 µm (see Figure 4-15).

Desilter: a cyclone separator similar to the desander but designed to remove solids larger than 15-25 µm.

Centrifuge: increases the rate of settling for particles in a water- diluted drilling fluid; it removes particles larger than 3-10 µm (see Figure 4-16).

Mud Cleaner: a desander for a weighted mud. The weighting material (barite) passes through with the mud; cuttings and fines are separated.

Figure 4-17 is a flow sheet of a typical mud treatment system which also dilutes the mud and cuttings before disposal.


AIR DISCHARGE
FEED

Spray Discharge

FIGURE 4·15
DESANDER CYCLONE
SEPARATOR

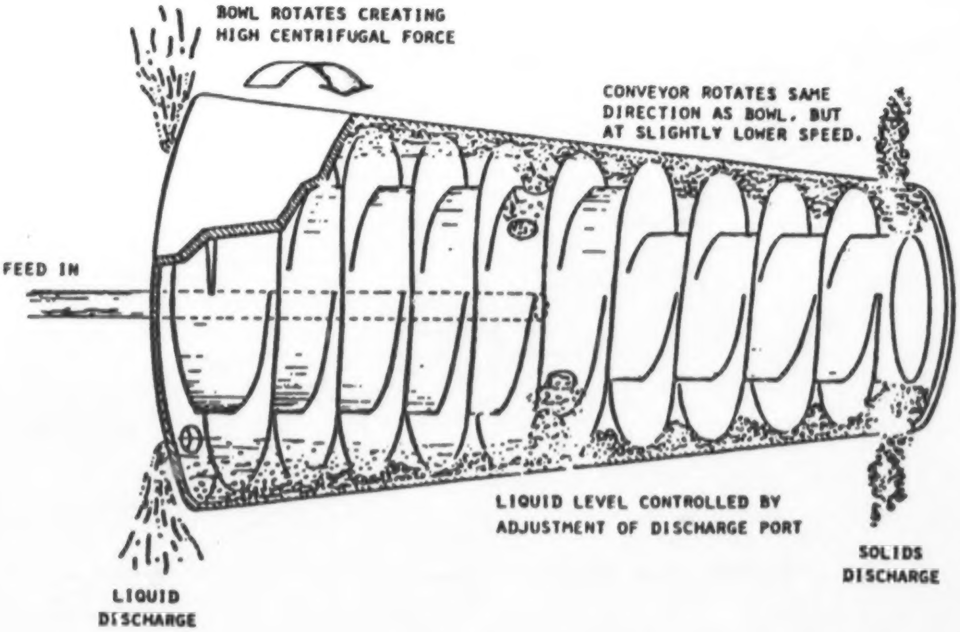
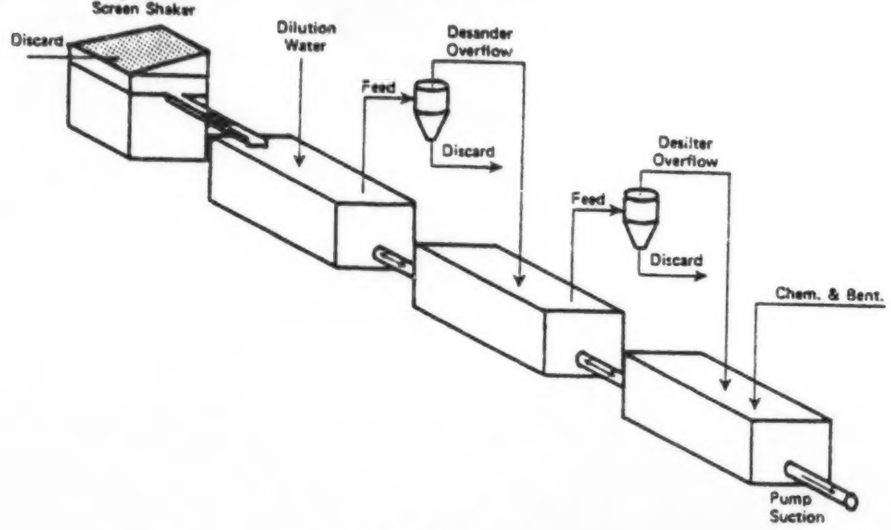

BOWL ROTATES CREATING HIGH CENTRIFUGAL FORCE
CONVEYOR ROTATES SAME DIRECTION AS BOWL, BUT AT SLIGHTLY LOWER SPEED.
FEED IN
LIQUID LEVEL CONTROLLED BY ADJUSTMENT OF DISCHARGE PORT
SOLIDS DISCHARGE
LIQUID DISCHARGE

FIGURE 4·16
CENTRIFUGE

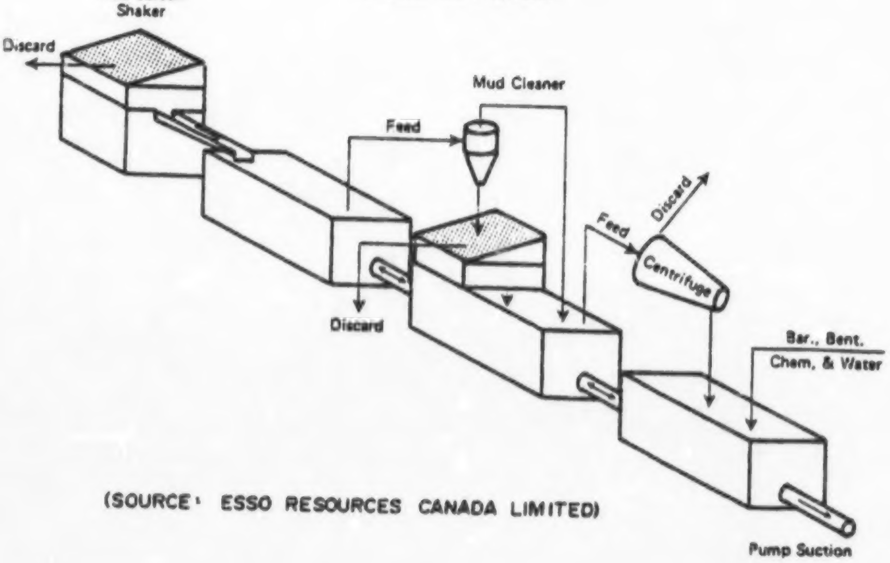
(SOURCE: REEF MUD, 1981)

FIGURE 4·17
FLOW SHEET OF MUD TREATMENT (SOLIDS CONTROL) SYSTEM

Unweighted Mud System


Rig or Fine Screen Shaker
Discard
Dilution Water
Desander Overflow
Feed
Discard
Desilter Overflow
Feed
Discard
Chem. & Bent.
Pump Suction

Weighted Mud System


Fine Screen Shaker
Discard
Mud Cleaner
Feed
Discard
Feed
Discard
Centrifuge
Bar., Bent.
Chem. & Water
Pump Suction

(SOURCE: ESSO RESOURCES CANADA LIMITED)

1.2.2 Oil-Base Muds and Cuttings

When oil-base muds are used, only enough is made to fill the mud tanks and hole as it is being drilled. As with water-base muds, oil-base muds are circulated through cuttings cleaning equipment to remove drilled solids. As with all drilling mud, the circulating mud is eventually contaminated by a build-up of solids so fine that no known method of processing will remove them (Kelly _et_ _al_. 1980). Such contamination is treated by dilution which results in the disposal of excess oil-base mud. A number of methods have been used:

(i) Mud company buys back the used mud which they haul to shore where it is cleaned and re-used.

(ii) Mud is mixed with diesel and burned in a modified well test burner. "All hydrocarbons are burned completely and the fallout is a fine non-polluting powder comprising mud products and fine drilled solids" (Kelly _et_ _al_. 1980).

(iii) Mud is treated with additional solids-suspending agent and used as a packer fluid (Kelly _et_ _al_. 1980).

A summary of methods used in the various areas is set out on Table 4-9.

In the North Sea, drill cuttings contaminated with oil-base mud are treated in cuttings cleaners by spray or immersion (Kelly _et_ _al_. 1980). The cleaned cuttings are then conducted through a sluice way to a depth somewhat below the water level and discharged into a contained water area inside a larger pipe (see Figure 4-18). Oil and solvent remaining on the tailings are released and rise in the quiescent zone between the two pipes. This oil is pumped to a separator from which the oil is returned to the mud system. In one application a 25-cm diameter sluice was run inside a 50-cm diameter flume extending to within 10 m of bottom (Cranfield no date).

The cuttings washer system, using the complete immersion method is best illustrated by the equipment developed and sold by Brandt Co. and Drexel Co. Figure 4-19 is a sketch of the Brandt cuttings washer. The cleaning process uses chemical cleaners which are relatively non-toxic and are compatible with the drilling systems used. Saturated cleaning solution is dumped into the active mud system (Brandt 1980).

An example of an operation using the spray method is as follows: "Cuttings are separated from the oil-mud system by the rig shaker. The cuttings drop down a chute and are led onto the shaker and sprayed by a system of jets with wash solution

TABLE 4-9

EXISTING OFFSHORE TREATMENT TECHNOLOGIES OIL-BASE MUD AND CUTTINGS

OFFSHORE AREA	TREATMENT TECHNOLOGY
Gulf of Mexico	Oil-base mud is hauled to shore and processed for re-use. Cuttings may be hauled to shore for disposal in a landfill site or cleaned in a water-spray cuttings cleaner and discharged.
California	Oil-base mud is hauled to shore and processed for re-use. Cuttings are hauled to shore for disposal in a land fill site.
Cook Inlet	No information.
North Sea - United Kingdom	Oil-base mud is hauled to shore for re-use. Cuttings are cleaned in a one-, two-, or three-stage cuttings washer, using diesel, diesel and water or surfactant to remove the oil. Cuttings are then discharged through a sea sump. Other systems in use include centrifugation and distillation to remove diesel oil from cuttings.
North Sea - Norway	Oil-base mud may be hauled to shore or incinerated through a horizontal flame; clean drill solids fall into the water. Cuttings are washed in a three-stage cuttings washer. In the first stage, a diesel wash removes the mud, in the second stage a detergent wash removes the diesel and in the third stage water removes the detergent. Cuttings are discharged through a sea sump.

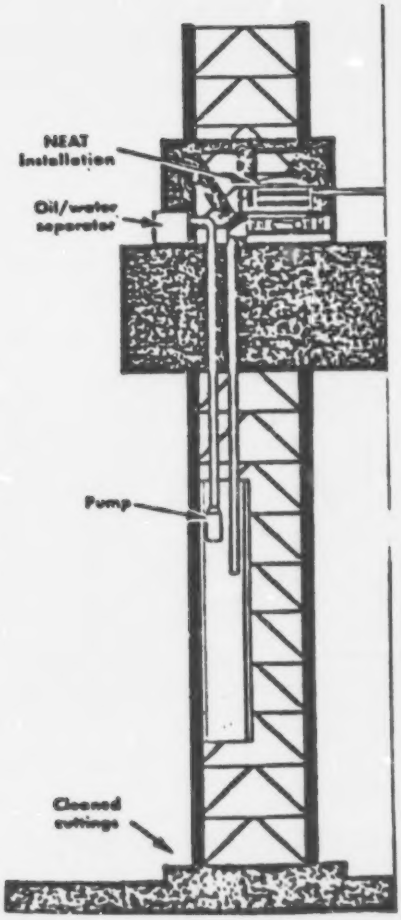

NEAT Installation
Oil/water separator
Pump
Cleaned cuttings

FIGURE 4·18
NORTH SEA OIL- BASE
CUTTINGS DISPOSAL
(SOURCE: CRANFIELD, NO DATE)

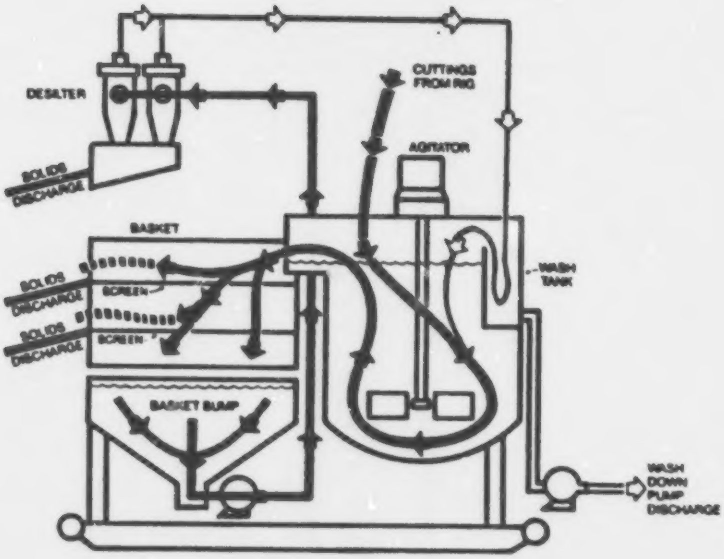

DESILTER
CUTTINGS FROM RIG
AGITATOR
SOLIDS DISCHARGE
BASKET
SOLIDS DISCHARGE
SCREEN
SOLIDS DISCHARGE
SCREEN
WASH TANK
BASKET SUMP
WASH DOWN PUMP DISCHARGE

FIGURE 4·19
BRANDT OILY CUTTINGS WASHER

(SOURCE: THE BRANDT CO., 1980)

containing 20% solvent. The wash solution returns to the holding tank; the sprayed cuttings drop into a flume and are subjected to seawater sprays that wash them onto the ocean floor. Oil will separate in the flume and be sucked off by a submersible pump to an oil/water separator" (Holder 1982). Figure 4-20 is a flow diagram for the system installed by Drexel in the Norwegian North Sea.

Equipment and systems manufacturers generally indicate that these systems can remove oil from cuttings so as to "meet present and proposed future legislation showing better than 1% free hydrocarbons when agitated in water and as low as 1.5% by weight when tested by the retort method" (Drexel 1982). Operators who are using these systems claim residual oil on cuttings amounts to 10-15% by weight (Wilkinson 1982; pers. comm. Johnston). A complete record of actual performance may be found in Table 2 - 19.

Cuttings cleaning equipment is usually supplied by the service company which owns and operates the equipment. "For a 30-day well the cost of washing cuttings is about $2,500./day. For an average oil mud interval of 9,615 ft. this is approximately $7.90/ft. of hole drilled" (Holder 1982).

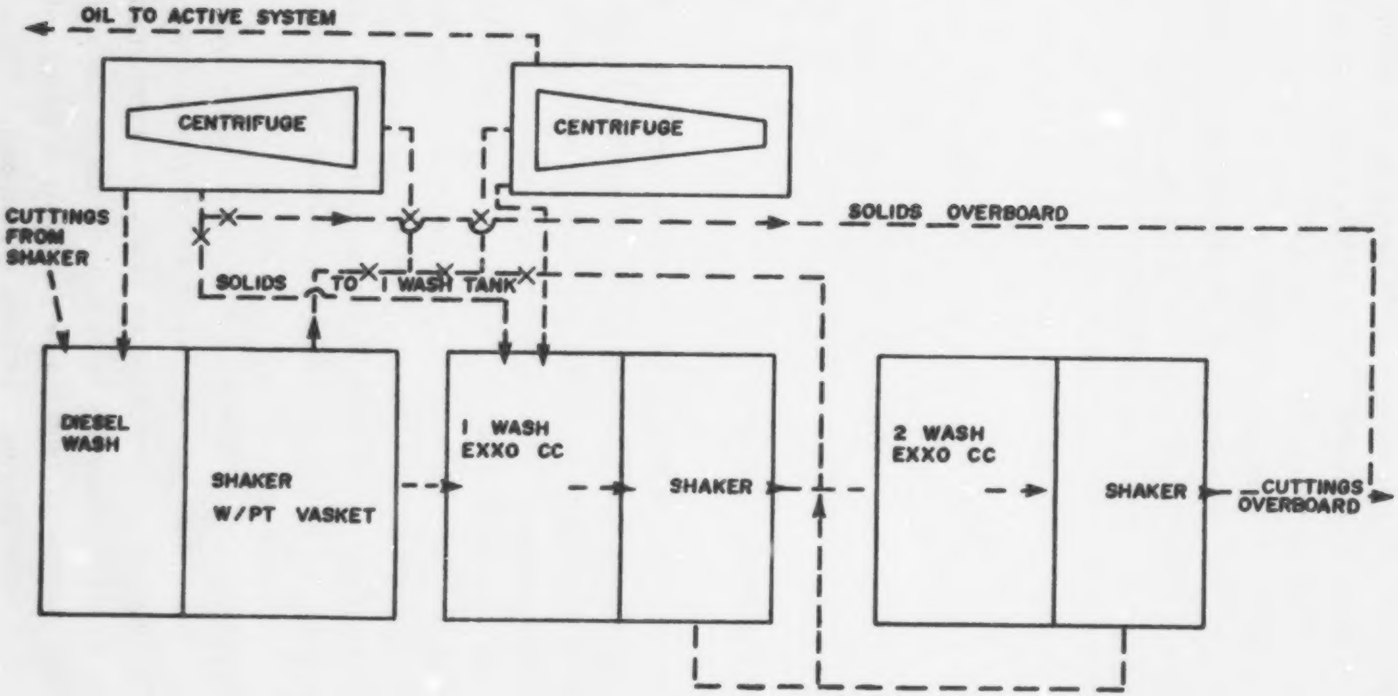
1.2.3 Miscellaneous Drilling Wastes

Miscellaneous drilling wastes include excess cement, blowout preventer fluid and well completion and workover fluids. Cement and BOP fluid are not treated before disposal on the ocean floor. The characteristics and discharge rates of these materials have been described in Chapter 2, Section 6.

It is reported that calcium bromide-zinc bromide emulsifies easily with crude oil (Spies et al. 1980). When the well is turned onto production, the fluid lost to the formation is produced with the oil or gas and is treated with the produced water. This fluid will often cause upsets in the water treatment equipment (pers. comm. Caudle). Fluid not lost to the formation is saved and re-used, because of its high cost.

Acids are usually neutralized by the formation and are produced together with oil or gas. This material ends up in the produced water and is treated and disposed of together with the produced water. The water, methanol or CO_2 used as a gelled suspending fluid is reproduced with the oil or gas within three days (Lillies 1982). This material is vented as a gas (CO_2) or mixed with the produced water (methanol and water) for final treatment and disposal.

FIGURE 4·20
FLOW DIAGRAM FOR DREXEL OILY CUTTINGS
WASH SYSTEM — NORTH SEA


OIL TO ACTIVE SYSTEM
CENTRIFUGE
CENTRIFUGE
CUTTINGS FROM SHAKER
SOLIDS OVERBOARD
SOLIDS TO 1 WASH TANK
DIESEL WASH
SHAKER W/PT VASKET
1 WASH EXXO CC
SHAKER
2 WASH EXXO CC
SHAKER
CUTTINGS OVERBOARD

(SOURCE: CRANFIELD, NO DATE)

1.3 Sanitary and Domestic Wastes

Sanitary wastes include human body waste discharges from toilets and urinals, whereas domestic wastes include materials discharged from sinks, showers, laundries and galleys (Federal Register 1981). Sanitary and domestic wastes are usually segregated on offshore platforms.

Sanitary wastes are discharged after treatment in a marine biological treating unit (see Figure 4-21) and chlorination to maintain a residual chlorine of at least 1 mg/L. This applies in most areas for which information is available (see Table 4-10). Domestic wastes are discharged directly following comminution. For facilities continuously manned by 9 or fewer persons in the Gulf of Mexico, the only requirement is that no floating solids be visible from the discharge.

"The marine biological sewage unit processes sewage and waste material by first aerating the material to allow bio-degradation, converting the sewage to carbon dioxide and ash. The digested waste next flows to a clarification tank where the solids (activated sludge) settle out and are returned to the aeration tank for added digestion. Clarified liquid is discharged into a chlorination contact chamber and is disinfected. After disinfection it is ready for discharge. Each manufacturer of a treating unit employs slightly different designs of their units, but follow the above principles" (Prokop 1981).

A minimum chlorine residual of 1.0 mg/L after a minimum retention time of fifteen minutes is required in permit conditions.

Offshore operators could not provide any performance information for installed units; however, Red-Fox Industries which supplies one of the most commonly used units provided a report of tests conducted on a Red-Fox Model RF-1000-M Marine Sanitation System. Influent suspended solids averaged 919 mg/L for the period of testing, with effluent suspended solids having an arithmetic mean for 40 samples of 26 mg/L. The arithmetic mean of influent BOD_5 was 798 mg/L and analysis of the 40 effluent BOD_5 samples had an arithmetic mean of 10 mg/L. The arithmetic mean of 40 effluent fecal coliform samples analysed by the membrane filter technique was 50 per 100 mL. These data are well within limits described in the regulations (National Sanitation Foundation 1979).

Estimates of costs for sanitary waste treatment are shown in Table 4-11.

Solid wastes are separated into refractory and non-refractory wastes. Galley garbage is separated from glass, metal, plastic and paper. It is pulverized and

TABLE 4-10

EXISTING OFFSHORE TREATMENT TECHNOLOGIES
SANITARY AND DOMESTIC WASTES

OFFSHORE AREA	TREATMENT TECHNOLOGY
Gulf of Mexico	Sanitary waste is treated in an extended aeration biological oxidation unit and then chlorinated to maintain a chlorine residual of 1.0 mg/L. Domestic wastes are dumped over the side, usually following comminution, and must comply with "no surfactants, dispersants, detergents, floating solids or foam" requirement (Federal Register 1981).
California	Sanitary waste is treated in an extended aeration biological oxidation unit and chlorinated to maintain a residual chlorine concentration of 1.0 mg/L. Domestic wastes are dumped over the side, usually following comminution and must comply with "no surfactants, dispersants, detergents, floating solids or foam" requirement.
Cook Inlet	No information.
North Sea - United Kingdom	Sanitary waste is treated in activated sludge unit. Domestic waste (wash and laundry) is chlorinated and discharged overboard.
North Sea - Norway	No information.

TABLE 4-11

ESTIMATED TREATMENT PLANT COSTS FOR SANITARY WASTES FOR OFFSHORE LOCATIONS, PACKAGE EXTENDED AERATION PROCESS (THOUSANDS OF 1983 CANADIAN DOLLARS)

	TREATMENT PLANT CAPACITY (Litres/day)		
	7,600	15,200	22,700
Capital Cost	45,000	57,000	70,000
Total Annual Costs	15,030	19,050	23,400
Financial	9,000	11,400	14,000
Operation & Maintenance	5,130	6,500	8,000
Energy & Power	900	1,150	1,400

Source: Train et al. 1976.

Escalated using ENR Cost Index and converted on basis of $0.8 US/$1. Cdn.

Standard MSD

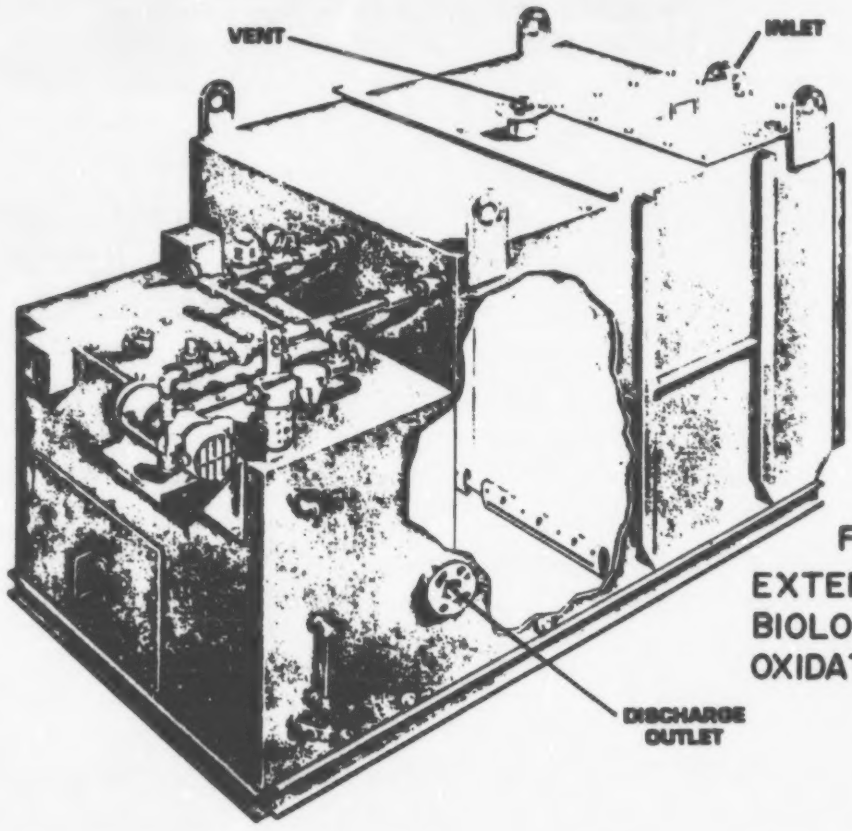
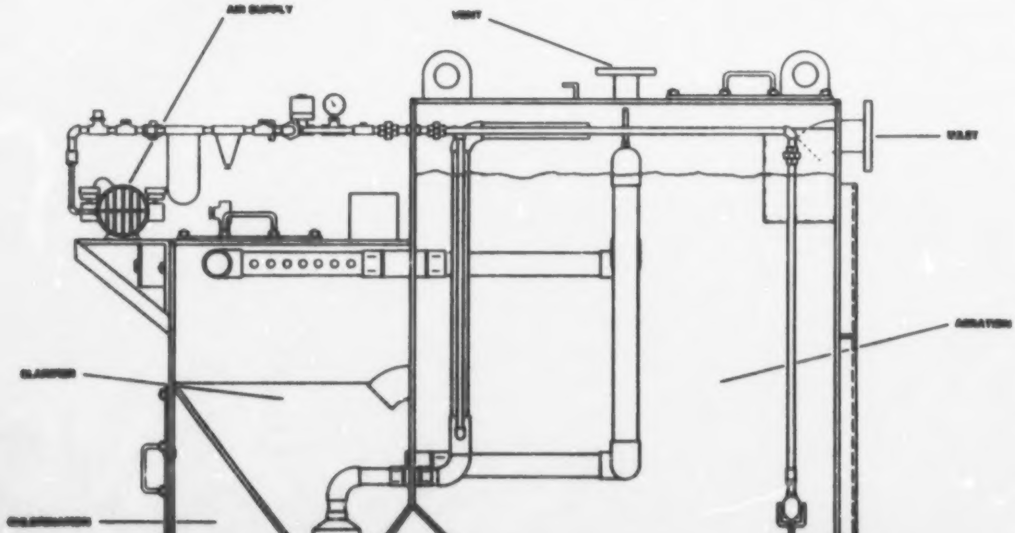

VENT
INLET
DISCHARGE OUTLET

FIGURE 4·21
EXTENDED AERATION
BIOLOGICAL
OXIDATION UNIT


AIR SUPPLY
VENT
INLET
AERATION
CLARIFIER
CHLORINATION

(SOURCE: RED FOX INDUSTRIES, 1982)

dumped overboard. Rags, cloth, paper cartons and goods, metal cans, bottles, glass, and plastic are collected and back-hauled to shore (Manning 1974). Sludge from sewage treatment plants is usually discharged to the sea. At the Murchison field in the North Sea, galley waste including vegetable matter is compacted and hauled to shore for disposal (Pappworth 1979).

1.4 Miscellaneous Discharges

Miscellaneous discharges from offshore oil and gas production platforms include:

- discharge from desalination units
- cooling water discharge
- fire control system test water.

Three types of desalination plants are commonly used on production platforms: (1) vapour compression, (2) reverse osmosis and (3) evaporative units (Sarma 1982). Simplified flow sheets for these units are shown in Figure 4-22.

The vapour compression unit is the most widely used type on offshore platforms (Sarma 1982). The waste discharge from these units is usually sea water which has been concentrated by a factor of two, plus sodium sulphite that has been converted by oxygen in the feed to sodium sulphate. Occasionally, acid is injected into the units for dissolving scale (Sarma 1982). Waste water from an evaporative unit would be similar to that from a vapour compression unit.

A once-through cooling water system is used almost without exception on offshore production platforms. It is designed to optimize the increase in water temperature by setting off pumping costs against increases in exchanger costs. The outlet water temperature is limited to 35° to 40°C to avoid scaling and corrosion (Sarma 1982; pers. comm. Holliman).

A completely independent firewater system is normally provided on production platforms, although the cooling water circuit may be connected by a manual valve to provide backup in the event of firewater pump failure (Sarma 1982).

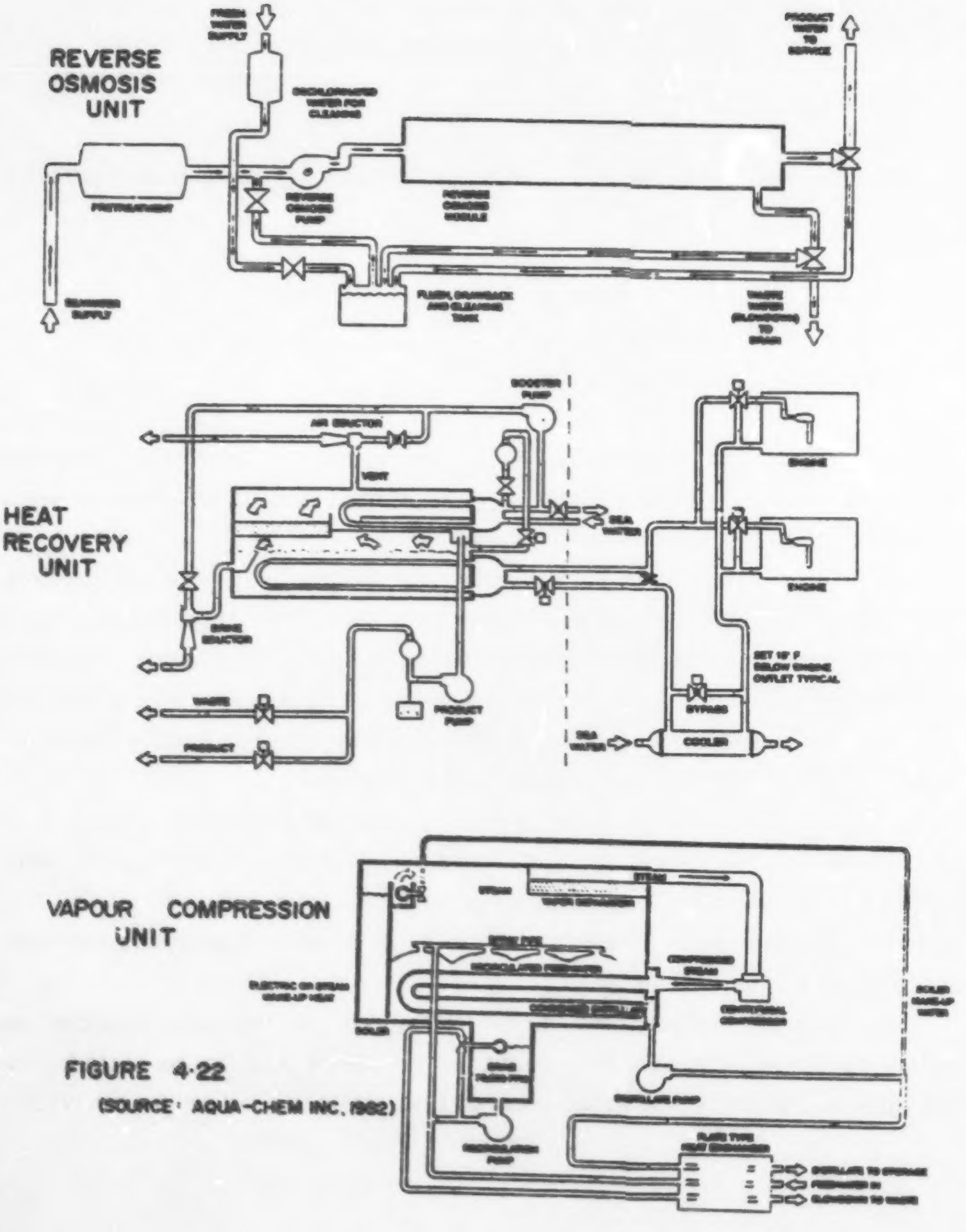

REVERSE OSMOSIS UNIT
FRESH WATER SUPPLY
PRODUCT WATER TO SERVICE
PRETREATMENT
REVERSE OSMOSIS PUMP
REVERSE OSMOSIS MODULE
SEAWATER SUPPLY
FLUSH, DRAWBACK AND CLEANING TANK
WASTE WATER (BLOWDOWN) TO DRAIN
HEAT RECOVERY UNIT
BOOSTER PUMP
AIR EDUCTOR
VENT
SEA WATER
ENGINE
ENGINE
BRINE EDUCTOR
SET 10° F BELOW ENGINE OUTLET TYPICAL
WASTE
PRODUCT
PRODUCT PUMP
BYPASS
SEA WATER
COOLER
VAPOUR COMPRESSION UNIT
STEAM
STEAM
COMPRESSED STEAM
ELECTRIC OR STEAM MAKE-UP HEAT
BOILER
CENTRIFUGAL COMPRESSOR
BOILER MAKE-UP WATER
DISTILLATE PUMP
PLATE TYPE HEAT EXCHANGER
DISTILLATE TO STORAGE
FEEDWATER IN
BLOWDOWN TO WASTE

FIGURE 4·22

(SOURCE: AQUA-CHEM INC. 1982)

2.0 State-of-the-Art Treatment Technologies

"State-of-the-art" describes a treatment process which is not widely used, but is in an advanced stage of development, and must be custom-designed and built.

2.1 Oily Water Wastes

The international oil industry has concluded that "the best practicable technology for treating production water is gravity separation followed by gas flotation" (Tramier 1982). They further concluded that the current use of granular media or fibrous bed coalescers for de-oiling production water is limited because of operating and maintenance difficulties.

The conventional downflow granular-bed pressure filter comprises a bed of media consisting of different sized particles of silica sand, anthracite coal and garnet. The solids loading capacity ranges from 2.5 to 7.0 kg/m^2 of filter area while flows range up to 3.4 $L/s/m^2$. Variations of this unit are the high-rate downflow and upflow units. These units have flow ranges up to 8 $L/s/m^2$ and solids handling capacities up to 50 kg/m^2. (U.S. Filter 1982).

Onshore filter operation has resulted in effluent qualities of from 0 to 2 mg/L oil (Evers 1975). Some manufacturers claim 96% removal of oil. If flotation is used upstream to reduce oil content to 50 mg/L, then the dual media filter can reduce oil content to 2 mg/L. It is important to emphasize that this performance is based on the presence of oil as insoluble drops which exceed a certain diameter.

Backwash of the filters is achieved by air or gas scour for two minutes, followed by wash at 10 $L/s/m^2$ for three minutes. In many applications a multi-wash cycle is necessary to maintain media bed efficiency because operating experience shows that the small droplets of oil will release into clean water better than into an oil/water mixture already containing droplets. It is estimated that 70% of the oil present is removed by each wash cycle (Serck Baker 1982).

Oil removed by this cycle is concentrated in the wash water by a factor of 2 or 3 so that backwash water contains 20-30 mg/L of oil as compared to 10 mg/L in the produced water (Serck Baker 1982).

The Hi-Rate or Deep Bed Media Filter will work best on certain types of oils; these are generally in the mid viscocity range (up to 9 degrees API gravity). Materials such as tars or heavy crude oil may form an impervious layer across the media surface giving short cycle lengths and poor backwash. Low viscosity hydrocarbons on the other hand may pass through the media bed with little retention (Serck Baker 1982).

In many cases the fine media (0.3 mm garnet) will remove 95% of particles down to 6 μm and the coarse media (0.45 mm anthracite) will have the same effectiveness for particles down to 15 μm (Udwin 1971).

The effectiveness of filters in removing non-soluble oil depends on physical properties of the suspended oil such as particle size, viscosity and gravity. It is therefore impossible to state, for example, that filtration will reduce oil content of produced water to x mg/L. When asked to write a guarantee of performance the filter manufacturer will usually ask for the suspended oil particle size and physical properties; this type of information is rarely, if ever, available.

An experimental oil filter-coalescer using reticulated polyurethane foams for treating oily water was tested in 1974. These tests of a 2.5 L/s bench-scale unit and a 13 L/s full-scale unit demonstrated excellent oil scavenging capabilities without foam clogging or degradation over reasonable time periods (Gollan and Fruman 1974). This development has a parallel in a commercial unit now in limited operation in West Texas and New Mexico water floods.

The heart of this separator is an open-celled foam that removes oils and solids due to wettability, not by pore size filtration. As the produced water passes through the foam, the oil and solids contact strands of the foam and adhere to the strands, rather than pass on with the water. When the foam becomes laden with oil and solids, a differential pressure switch initiates the regeneration cycle causing the inlet and outlet valves to close and water to be pumped into the rear of the vessel. This causes the foam pack to be squeezed, and forces captured oil, solids, and water from the front of the vessel. The oil, solids and water in this mixture are easily separated by gravity.

There is limited capital cost information available for this type of unit, but what is available suggests that the capital cost would be comparable to a filter of the same capacity. No information is currently available on the costs of operation.

2.2 Drilling Fluids and Cuttings

The discharge of oil-base drilling fluid is prohibited in all areas being reviewed. In the Gulf of Mexico and California drill cuttings can be discharged provided there is "no discharge of free oil" which means no surface sheen or bottom emulsion. The existing cuttings washing systems discussed in Section 1.2.2 of this chapter will reduce the oil content to between 3 wt.% and 15 wt.%. This performance may not be adequate in the future because of the potential for environmental impact, although washed cuttings discharge continues to take place in the North Sea. Discussions with Gulf of Mexico operators, where the use of oil-base mud is much more limited, suggested that hauling cuttings to shore for landfill disposal was the currently preferred option.

Three systems in the development stage are an order of magnitude better than conventional systems at removing oil from cuttings (pers. comm. Grubbs).

(i) Crew Process: the cuttings are fed to a vacuum retort where they are ground to a fine powder (100-120 μm) and heated to a temperature of 350°C. A two-stage vacuum pump moves the evaporated water, oil and chemicals through a cyclone into a vapour condenser. The condensed vapour is returned to the active mud system by a pump. The powdered cuttings, containing less than 1% oil, can be dumped over the side (Anon. 1982b).

(ii) Swaco Process: hot air (at 320°C) is passed through cuttings on a vibrating screen which evaporates the oil and water. Cuttings falling off the vibrating screen contain less than 1% oil and can be dumped over the side (pers. comm. Grubbs).

(iii) Critical Fluid Systems Process: uses liquefied gases as a solvent for extracting residual oil from cuttings (carbon dioxide or freon). The treated cuttings are reported to contain less than 1% oil by weight. Some test runs have achieved results as low as 0.01% by weight (pers. comm. deFillippi).

No cost information was available on these three developing processes. The current status of these systems is described in Table 4-12.

TABLE 4-12

STATUS OF DEVELOPMENT AND MARKETING FOR THREE STATE-OF-THE-ART SYSTEMS FOR REMOVING OIL FROM CUTTINGS

PROCESS SYSTEM	DEVELOPMENT	MARKETING
Crew	5 years development; built and tested a field unit and obtained a patent. Three units being installed in the North Sea[1]	Hughes is presently reviewing its position and whether they wish to pursue this business[4]
Swaco	Built and tested a prototype.[2]	Not ready for market
Critical Fluid Systems	Completed bench scale development. Did a process design and developed costs for a prototype[3]	Not ready for market.

References:
1. Anon. 1982b
2. pers. comm. Grubbs
3. pers. comm. deFillippi
4. pers. comm. McMordie

2.3 Other Wastes

Extended aeration biological treatment of sewage has not been successful in those locations where there are no living quarters (Martin and Schmidt 1973). Workers are often on the platform in large numbers at irregular intervals (perhaps one week on, 2 to 3 weeks off). The extended aeration unit is consequently incapable of maintaining a healthy biological growth due to lack of food.

Similarly, it has been reported that "the most critical factor affecting the efficiency of extended aeration plants in isolated situations is the time they take to establish a good activated sludge, and achieve full treatment efficiency". Alaskan experience has found that start-up periods of at least 60 to 90 days are necessary (Petwa Canada Ltd. 1982).

The rotating biological contactor (RBC) has been developed as an alternative to the extended aeration unit..

The RBC consists of closely-spaced plastic discs fixed on a shaft and submerged 30% to 45% in the waste water being treated. When the shaft rotates the biomass is alternately submerged in the waste and exposed to oxygen in the atmosphere. The biomass which is reported to have a "mixed liquor suspended solids" concentration of 10,000 to 20,000 mg/L is 1 to 4 mm thick. Consequently the retention times required are 60 to 90 minutes for the same treatment as obtained with the extended aeration treatment system having a 24-hour retention time.

Effluents from the RBC zone will generally contain 100 to 150 mg/L suspended solids, most of which is biological mass that has fallen off the discs. A clarifier separates these solids and thickens them to 3 or 4% concentration if required. The clarified effluent typically contains 10 to 20 mg/L of BOD.

Because RBC media shafts are essentially individual units, the cost of large RBC units is greater than extended aeration units which exhibit economics of scale. The RBC uses 5.6 KW for a 7.5 m shaft and requires about 1.0 hour a week for maintenance.

RBC compares with extended aeration as follows (Petwa Canada 1982):

RBC	EXTENDED AERATION
Higher capital cost	Relatively low capital cost
Short start-up period	Long start-up period
Does not require a skilled operator	Requires a skilled operator to maintain good treatment
If over-designed effluent quality is better than design; and if over-loaded still provides good treatment	If over- or under-designed it will not perform properly; effluent quality deteriorates when over-loaded

3.0 Comparison of Offshore and Onshore Treatment Facilities

3.1 Introduction

This section compares the use of existing waste treatment technologies on an offshore platform with their use on a vessel or at onshore facilities. The relative advantages, disadvantages and costs of the different locations are presented.

Construction cost experience for offshore and onshore treatment facilities in Northern Alaska, on Melville Island in the High Arctic and in the North Sea show that the installed cost of facilities is many times that for settled areas such as the Gulf of Mexico, for the following reasons:

- communication is difficult;
- access is limited and difficult;
- material and information shortages create many lengthy delays;
- the cost of delays is greater because of limited infrastructure;
- infrastructure costs are allocated entirely to the job;
- transportation and handling of materials is more costly;
- labour efficiency is adversely affected by inclement weather;
- premium labour rates must often be paid to attract workers.

For the purpose of this evaluation the following cost relationships as reported in the literature have been used:

Cost in North Sea = Cost in Gulf of Mexico x 2.5 (Kulachol 1980)
Cost in Ice-Infested Water = Cost in Gulf of Mexico x 4.0 (Kulachol 1980)
Cost installed on a barge = Cost on land in developed area (Unrug 1979)

Costs for Scotian Shelf and North Sea platforms have been assumed to be equal. The assumed treatment technology used for the comparison is shown in Table 4-13.

Tables 4-14, 15 and 16 show a comparison of the advantages and disadvantages of treatment on an offshore production platform with a vessel moored near the platform and with transportation to land for on-land treatment. Some of the combinations are not feasible because of freezing conditions, obviously high cost, or unproven technology.

TABLE 4-13

ASSUMED TREATMENT TECHNOLOGY
EQUIPMENT OR SYSTEM USED TO MEET TREATMENT STANDARD

WASTE STREAM	TREATMENT STD.	OFFSHORE ON PLATFORM	OFFSHORE ON VESSEL	ONSHORE ON LAND
Produced Water, Sand and Completion Fluids	Removal of insoluble oil to a level of 50-100 mg/L in produced water	Settling tank and flotation system mounted on platform	Settling tank and flotation system mounted on vessel moored at site and connected to platform by pipeline	Pipeline to shore with settling tank and flotation system mounted on land
Ballast and Displacement Water	Removal of insoluble oil to a level of 10 mg/L in water	Plate coalescer mounted on platform	Plate coalescer mounted on vessel moored at site and connected by pipeline to platform	Pipeline to shore with plate coalescer mounted on land
Deck Drainage	"No discharge of free oil"*	Skim pile mounted on platform	Skim pile mounted on moored vessel and connected by pipeline to platform.	Not feasible at this time.
Sanitary Waste	No floating solids and 1 mg/L residual chlorine	Biological oxidation and chlorination unit mounted on platform	Biological oxidation and chlorination unit mounted on vessel and connected by pipeline to platform	Transport to shore by supply ship
Water-Base Mud and Cuttings	-	Regular mud cleaning system mounted on platform for separation of drill solids from mud	Regular mud system mounted on moored vessel and connected by pipeline to platform	Store mud on platform and haul to shore for clean-up and waste disposal
Oil-Base Mud and Cuttings	"No discharge of free oil"*	Two-stage cuttings washer system mounted on platform	Two-stage cuttings washer system mounted on moored vessel and connected to platform by pipeline	Cuttings collected and hauled to shore for landfill disposal

NOTE: (*) "No discharge of free oil" means no surface sheen or bottom emulsion

TABLE 4-14

COMPARISON OF OFFSHORE AND ONSHORE WASTE TREATMENT FOR THE SCOTIAN SHELF

	LOCATIONS OF TREATMENT UNIT			
WASTE STREAM	**TREATMENT STD. TECHNOLOGY**	**OFFSHORE ON PRODUCTION PLATFORM**	**OFFSHORE ON VESSEL**	**ONSHORE ON LAND**
Produced Water, Sand and Completion Fluids	N/A	--	--	N/A
Ballast and Displacement Water	N/A	--	--	N/A
Deck Drainage	Skim pile for removal of insoluble oil to comply with "no discharge of free oil"*	--	Adds considerably to the design deck load and hence the cost	Not feasible at this time because of cost of pipeline to shore
Sanitary Waste	Biological oxidation for solids and BOD removal followed by chlorination for bacteria control	Cost of space on platform is expensive	1) Performance is inhibited by motion which makes unit larger and more expensive 2) Mooring of floating unit and pipeline transfer system are costly	Not practical nor feasible at this time because of distance to shore and cost of pipeline
Water-Base Drilling Mud and Cuttings	Mud cleaning system for separation of cuttings from drill fluid	Cost of space on platform is expensive Only required for 2-4 years in early life of field	--	1) Transfer to land in hoppers for clean-up and re-use is expensive 2) Availability of disposal site may be a problem
Oil Base Cuttings	Cuttings cleaning system for removal of oil from cuttings to comply with "no discharge of free oil"*	Space on platform is expensive Only required for 2-4 years in early field life	—	Availability of disposal site may be a problem

* "No discharge of free oil" means no surface sheen or bottom emulsion

TABLE 4-15

COMPARISON OF OFFSHORE AND ONSHORE WASTE TREATMENT FOR THE GRAND BANKS

WASTE STREAM	TREATMENT STD. TECHNOLOGY	LOCATIONS OF TREATMENT UNIT		
		OFFSHORE ON PRODUCTION PLATFORM	OFFSHORE ON VESSEL	ONSHORE ON LAND
Produced Water, Sand and Completion Fluids	Settling tank followed by gas flotation for removal of insoluble oil to 50-100 mg/L	1) Space on platform is costly in deep, iceberg-infested water 2) Need to provide space and capacity now for unknown future volumes and composition changes	1) Performance is inhibited by motion which makes unit larger and more expensive 2) Floating unit and mooring system has to be moveable which is new technology and hence expensive	1) Pipeline to shore is new technology and cost is higher. Must provide for future needs 2) Water disposal is more difficult and hence more expensive
Ballast and Displacement Water	Plate coalescer for removal of insoluble oil to a level of 10 mg/L	1) Space on platform is costly in deep water	1) Performance is inhibited by motion which makes unit larger and more expensive 2) Floating unit and mooring system has to be moveable which is new technology and hence expensive	1) Cost of pipeline to shore is high 2) Water disposal is more difficult and hence more expensive
Deck Drainage	Skim pile for removal of insoluble oil to comply with "no discharge of free oil"*	-	Adds considerably to the design deck load and hence to cost	Not feasible at this time
Sanitary Waste	Biological oxidation for solids & BOD removal followed by chlorination for bacteria control	Cost of space on platform is expensive	1) Performance is inhibited by motion which makes unit larger and more expensive 2) Floating unit and mooring system has to be moveable which is new technology and hence expensive	Not practical or feasible at this time because of distance to shore and freezing
Water-Base Drilling Mud and Cuttings	Mud cleaning system for separation of cuttings from drilling fluid	Cost of space on platform is expensive and only required for 2-4 years in early life of field	Transfer system would be new technology and therefore costly	1) Transfer mud and cuttings to land by all-season transport is new technology 2) Availability of disposal site may be a problem
Oil-Base Cuttings	Cuttings cleaning system for removal of oil from cuttings to comply with "no discharge of free oil"*	Space on platform is expensive and only required for 2-4 years in early field life	1) Transfer system in ice infested water is new technology and therefore expensive 2) Mooring system for vessel in ice is new technology and therefore expensive	1) Transfer of cuttings to land for disposal in landfill site by all-season transport is new technology 2) Availability of disposal site may be a problem

* "No discharge of free oil" means no surface sheen or bottom emulsion

TABLE 4-16

COMPARISON OF OFFSHORE AND ONSHORE WASTE TREATMENT FOR THE BEAUFORT SEA

WASTE STREAM	TREATMENT STD. TECHNOLOGY	LOCATIONS OF TREATMENT UNIT		
		OFFSHORE ON PRODUCTION PLATFORM	OFFSHORE ON VESSEL	ONSHORE ON LAND
Produced water, Sand and Completion Fluids	Settling Tank followed by Gas Flotation for removal of insoluble oil to 50-100 mg/L	1) Space on platform or island is high cost in deep water 2) Need to provide space and capacity now for unknown future volumes and composition changes	1) Performance is inhibited by motion which makes unit larger and more expensive 2) Mooring of floating unit and transfer system are costly and unproven technology in ice	1) Onshore construction in Beaufort not likely to be much less expensive than offshore 2) Pipelining is costly and technology is unproven 3) Any all-season transportation system is likely to be costly while technology is unproven 4) Water disposal is more expensive onshore
Ballast and Displacement Water	Plate Coalescer for removal of insoluble oil to a level of 10 mg/L	1) Space on platform or island is high cost	1) Performance is inhibited by motion which makes unit large and more expensive 2) Mooring of floating unit and transfer system are costly and unproven technology in ice	1) Onshore construction in Beaufort not likely to be much less expensive than offshore 2) Pipelining is costly and technology is unproven 3) Any all-season transportation system is likely to be costly while technology is unproven 4) Water disposal is more expensive onshore
Deck Drainage	Skim pile for removal of insoluble oil to comply with "no discharge of free oil"*		Adds considerably to the design deck load and hence cost	Not feasible at this time because of distance to shore and freezing
Sanitary Waste	Biological oxidation for removal of solids, BOD, followed by chlorination for bacteria control	Cost of space on platform or island is expensive	1) Performance is inhibited by motion which makes unit larger and more expensive 2) Mooring of floating unit and transfer system are costly and unproven technology in ice	Not practical nor feasible because of distance and freezing
Water-Base Drilling Mud and Cuttings	Mud cleaning system for separating cuttings from drill fluid	Cost of space on platform or island is expensive Only required for 2-4 years in early life of field	1) Transfer system in ice infested water is new technology and therefore costly 2) Mooring system for vessel in ice is new technology and therefore expensive	1) Transfer to land by all-season transport is new technology 2) Disposal in permafrost is new technology and may be a problem
Oil-Base Cuttings	Cuttings cleaning system for removal of oil from cuttings to comply with "no discharge of free oil"*	Space on platform or island is expensive Only required for 2-4 years in early life of field	1) Transfer system is new technology and therefore costly 2) Mooring system for vessel in ice is new technology and therefore expensive	1) All-season transportation system is new technology and therefore expensive 2) Burial in permafrost is new technology and may be a problem

* "No discharge of free oil" means no surface sheen or bottom emulsion

The cost of equipment on a vessel or on land can not be evaluated for the Grand Banks and Beaufort Sea situations because the technology is unproven. Design of the mooring system for a vessel in ice-covered water requires new and unproven technology and can only be estimated after a preliminary design study has been prepared.

A pipeline to shore in the Beaufort Sea or off the Grand Banks is also unproven technology, consequently costs can be estimated only after a preliminary design has been prepared.

The all-season transportation system that would be required for the four minor wastes is also new and unproven technology. The cost can be estimated only after conceptual design and preliminary engineering.

The Scotian Shelf systems are estimated by analogy with cost experience in the Gulf of Mexico and North Sea.

3.2 Produced Water Treatment

The capital cost of a produced water treatment system with capacity of 16,000 m^3/d has been estimated (Table 4-17).

TABLE 4-17

PRODUCED WATER HANDLING CAPITAL COST

	Cost ($1,000 CDN 1983)		
	Offshore on Platform	**Offshore on Vessel**	**Onshore on Land**
Plate Coalescer	1,040	420	420
Platform Space	1,000	-	-
Mooring System	-	50,000	-
Pipeline to Shore	-	-	400,000+
TOTAL:	2,040	50,420	400,420+

The impracticality of mounting treatment facilities on a vessel or piping to shore is evident.

3.3 Drilling Fluids and Cuttings

The cost of providing a three-stage cuttings cleaning system on an offshore platform to handle 7 m^3/d (12 t/d) of oil-base mud cuttings is given below (Table 4-18).

TABLE 4-18
OILY CUTTINGS HANDLING COST

	Cost (1,000 Cdn. $ 1983) Offshore on Platform
Cuttings Cleaning System	720
Platform Space	640
TOTAL:	1,360

The cost of cuttings disposal by haulage to shore from an exploratory well on the Georges Banks and burial in a landfill is reported to be $712 US/tonne (OOC 1981). This is probably accurate for a single well; however, a production platform with a continuing need can probably be handled at a lesser cost. A hauling and disposal cost for cuttings is estimated at $340/tonne (Anon. 1980; Anon 1982a). The annual cost to dispose of cuttings would therefore be about $1,500,000. The cuttings cleaning system clearly has the cost advantage.

This cost analysis suggests that, it would be more economical to handle the Scotian Shelf wastes by constructing waste treatment facilities on the platform. It is also apparent that this result could have been different were the development area located closer tc shore.

4.0 Applicability of Treatment and Disposal Methods to Canadian Offshore Areas

Table 4-19 lists six environmental and geographical conditions that affect the cost of treatment and disposal methods. A qualitative evaluation has been made of each condition relative to the Gulf of Mexico, California Coast, Cook Inlet, North Sea and the three Canadian offshore areas. The least and most favourable conditions have been identified and a qualitative ranking made of the seven areas. This table illustrates that, on the basis of cost, the ranking of treatment and disposal methods from most to least costly is:

- Grand Banks
- Beaufort Sea
- North Sea
- Scotian Shelf
- Gulf of Mexico and Cook Inlet
- Coast of California.

Results of this type of analysis are at best directional and illustrate primarily that treatment and disposal costs (which affect "best practical control technology") will be more expensive in Canadian offshore areas than in the United States and United Kingdom areas with which they are compared.

Table 4-20 identifies the physical constraints for applying existing treatment and disposal methods to the three Canadian offshore areas.

The major physical constraint in Canadian offshore areas is low temperature, which results in a requirement for temperature control or freeze protection for a majority of existing treatment and disposal methods.

Iceberg hazards on the Grand Banks could result in selection of a floating production system. If this selection is made, the ship motion which results will require gravity-type oil separation equipment to be increased in size.

Many existing disposal methods result in discharges at the sea surface. The existence of an ice cover may require that waste streams be disposed of below the ice surface.

TABLE 4-19

COMPARISON OF ENVIRONMENTAL/GEOGRAPHICAL CONDITIONS AFFECTING COST

		GULF OF MEXICO	COAST OF CALIFORNIA	COOK INLET	NORTH SEA	SCOTIAN SHELF	GRAND BANKS	BEAUFORT SEA
(1)	Distance to shore	0-200 km	<20 km +	<20 km +	120-500 km - oil 40-650 km - gas	200 km - gas	320 km - oil*	5-120 km - oil
(2)	Distance to industrial infrastructure	close	close	far *	close	close	close	far *
(3)	Design-basis sea state	moderate	moderate	moderate	severe *	severe *	severe *	moderate
(4)	Low ambient temperature	not a factor +	not a factor +	moderate	moderate	moderate	severe *	severe *
(5)	Ice conditions	none +	none +	50 cm sea ice	none +	none +	sea ice, icebergs*	1st year sea ice + 2m thick; multi-year ice islands *
(6)	Water depth	1 m - 300 m *	to 400 m *	to 60 m +	to 200 m *	to 50 m +	80 m	to 100 m
QUALITATIVE RANKING		2	1	2	5	4	7	6

* Least favourable

+ Most favourable

TABLE 4-20

PHYSICAL CONSTRAINTS TO APPLICATION OF EXISTING TREATMENT AND DISPOSAL METHODS

OILY WATER TREATMENT	SCOTIAN SHELF	GRAND BANKS	BEAUFORT SEA
Gravity separation (settling tank, plate coalescer)	Must protect from freezing	Must protect from freezing; for floating platform, motion reduces efficiency of oil separation; require larger unit to achieve same effluent quality	Must protect from freezing
Gas Flotation	Must protect from freezing	Must protect from freezing; for floating platform, motion reduces efficiency of oil separation; require larger unit to achieve same effluent quality	Must protect from freezing
Skim Pile (gravity separation and subsea disposal)	Must protect from freezing	Must protect from freezing; for floating platform, motion reduces efficiency of oil separation; require larger unit to achieve same effluent quality	Must protect from freezing
Mud and Cuttings			
Water-base	Must protect from freezing	Must protect from freezing and dispose of under ice	Must protect from freezing and dispose of under ice
Incineration of oil-base mud	-	During ice cover, ash falls onto ice	During ice cover, ash falls onto ice
Oil-base mud cuttings cleaning	Must be inside to protect from freezing; and ventilated for safety reasons	Must be inside to protect from freezing; and ventilated for safety reason	Must be inside to protect from freezing; and ventilated for safety reasons
Oil-base mud cuttings disposal	-	-	Disposal by burial in permafrost may be a problem and disposal in southern Canada is costly
Oil-base mud reuse	-	-	Too far to infrastructure
Sanitary Waste	Must keep temperature above 20ºC for biological activity	Must keep temperature above 20ºC for biological activity and dispose under ice cover	Must keep temperature above 20ºC for biological activity and dispose under ice cover
Miscellaneous Discharges	-	Must dispose of under ice cover	Must dispose of under ice cover

CHAPTER 4

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CHAPTER 4

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CHAPTER 5

REVIEW OF THE BIOLOGICAL EFFECTS OF PRODUCTION WASTES

1.0 Produced Water and Deck Drainage

Produced water can be the largest waste discharge associated with normal offshore hydrocarbon production activities. As indicated earlier (Chapter 2, Section 1.4), produced water typically contains high dissolved concentrations of sodium, calcium, magnesium, and some trace metals (usual concentration range <0.01 to 0.3 mg/L). Dissolved, emulsified and particulate crude oil constituents are also components of produced water; total oil concentration ranges from 25 mg/L to 50 mg/L under normal operating conditions. In addition, produced water contains low (1-100's mg/L) concentrations of organic chemicals used in treatment processes on the platform.

Deck drainage is also a source of hydrocarbon input to marine environments. Unlike produced water, deck drainage may include trace amounts of surfactants, dispersants and refined oil products. The biological effects of the latter discharges are only briefly discussed, because small waste volumes and low hydrocarbon concentrations are associated with offshore production.

The effects of produced water on marine flora and fauna have been examined in laboratory bioassays and several case studies of production fields. A comprehensive review of the ecological effects of produced water is under preparation for the American Petroleum Institute, but was unavailable for this study (Middleditch, in press). Recent studies completed in North Sea production fields were also not obtained in the time necessary for inclusion in this review. Concern has been expressed regarding individual, synergistic and antagonistic effects of the various constituents of produced waters, but the separation of component effects has not been possible in either case studies or laboratory bioassays. In production field case studies, the discharge of other wastes such as drilling fluids and deck drainage complicates delineation of the source of trace metals and hydrocarbons while there have been no laboratory studies which identify the cause of produced water toxicity. Regional variations in the content of produced water, as well as temporal changes in its composition during the life of a given well, have also complicated investigations on the effects of this production waste. Some or all of these constraints and the difficulty of establishing controls and baseline conditions have hampered most of the studies discussed in subsequent sections.

1.1 Acute Lethal and Sublethal Effects of Produced Water

A limited number of bioassays have been completed to determine the acute lethal toxicity of produced waters with marine species, and most of these laboratory investigations have used invertebrates as test organisms. The most recent and complete study was conducted by Rose and Ward (1981) with Buccaneer Field (Gulf of Mexico) produced water and shrimps (Penaeus axtecus and P.. setiferus), barnacles (Balanus tintinnabulum) and the crested blennie (Hypleurochilus geminatus). The lowest LC50 determined under 48-h static bioassay conditions, with an aerated medium to maintain a minimum dissolved oxygen content of 4 mg/L, was 8,000 ppm with larval brown shrimp (Table 5-1).

The results of bioassays with brine from Bryan Mound are also included in Table 5-1 because of the limited number of bioassays which have been conducted with produced water. This proposed petroleum storage site was created by pumping approximately 110,000 m^3 of sea water per day through the caverns to leach salt. The discharge was similar to produced water because its salinity and trace metal content were higher than in sea water. Howe (1981) reported 96-h LC50 values in the range from $53^{o}/oo$ to $57^{o}/oo$ salinity for adult and subadult shrimp . In other studies with this brine, redfish embryos and larvae were found to be slightly more sensitive (96-h LC50 45 to $50^{o}/oo$ salinity; Neff et al. 1981, cited in Owens et al. 1981).

All the published literature reviewed for this study indicates that produced water and brine are only slightly toxic (0.1% to 1%) to practically non-toxic (>1%) to most marine organisms, using standards commonly cited for describing acute toxicity (Sprague 1973, Ray 1978, both cited in Rose 1981). The limited toxicity data available for juvenile and larval stages of shrimp and fish suggest, however, that immature individuals may be more sensitive than adults to the effects of produced water. Further studies are required to substantiate this hypothesis.

The sublethal effects of produced water have also been examined during laboratory or field investigations. The sublethal responses observed during past investigations are summarized in Table 5-2, and generally suggest that detrimental effects would not occur at concentrations of produced water which could be reasonably expected near offshore discharge sites.

Laboratory studies of acute and sublethal toxicity suggest that most marine organisms can tolerate relatively short-term (<96 h) exposures to high concentrations of produced water without significant adverse effects. Longer term effects such as bioaccumulation of trace metals and hydrocarbons under field conditions are discussed in the following section.

TABLE 5-1

SUMMARY OF PRODUCED WATER ACUTE LETHAL BIOASSAY RESULTS
(96-h LC50 unless otherwise indicated)

ORGANISM	CONCENTRATION (%)	COMMENTS	REF.
INVERTEBRATES			
Palaemontes pugio shrimp	20	48 h	1
P. pugio shrimp	100		
Jassa falcata amphipod	10	48 h 100 percent mortality	2
Penaeus aztecus			3
brown shrimp larva	1	Static 48h; min D.O. 4 mg/L	
brown shrimp subadult	10	Static 48h; 18-25°C; min D.O. 4 mg/L	
brown shrimp subadult	4.4	Flowthrough; 25-29°C; min D.O. 4 mg/L	
brown shrimp adult	11	Static 48h; 18-25°C; min D.O. 4 mg/L	
Penaeus setiferus			3
white shrimp subadult	8.3	Static; 18-25°C; min D.O. 4 mg/L	
white shrimp subadult	6.2	Flow through; 22°C; min D.O. 4 mg/L	
white shrimp adult	6.8	Static; 18-25°C; min D.O. 4 mg/L	
white shrimp juvenile	>10		4
P. setiferus and *P. aztecus*			5
adult and subadult	57°/oo salinity	48 h	
subadult	53°/oo salinity		
Balanus tintinnabulum			3
barnacle	8.3	Static; 18-25°C; min D.O. 4 mg/L	
barnacle	0.8	Static; 18°C; min D.O. 0.5 mg/L	
barnacle	5.1	Flowthrough; 25-29°C; min D.O. 4 mg/L	
FISH			
Hypleurochilus geminatus crested blennie	25 0.7	Static; 22-25°C; min D.O. 4 mg/L Static; 24°C; min D.O. 1.2 mg/L	3
crested blennie	27		6
Sciaenops ocellata redfish embryos and larva	45-50°/oo salinity	toxic	7
stickleback	75-100		8

REFERENCES

1. Mackin and Coute (1971, cited in Mackin 1973)
2. Gallaway (1980)
3. Rose and Ward (1981)
4. Zein-Eldin and Keney (1978)
5. Howe (1981)
6. Gallaway and Martin (1980, cited in Gallaway 1980)
7. Neff *et al*. (1981, cited in Owens *et al*. 1981)
8. Dept. of Interior (1975, cited in Rose 1981)

TABLE 5-2

SUMMARY OF REPORTED SUBLETHAL EFFECTS OF PRODUCED WATER*

ORGANISM	LOCATION	RESPONSE	REFERENCE
INVERTEBRATES			
Balanus tintinnabulum barnacle	Buccaneer Field Gulf of Mexico	No difference in condition of animals taken 1 m from discharge and those from control stations.	Boland 1980, cited in Gallaway 1980
oysters	Louisiana	1% to 5% had no effect on pumping rates. 10% caused significant decrease in pumping rate but no mortality. Normal pumping rates returned when the animals were placed in clean sea water.	Lunz 1950, cited in Mackin 1973
oysters	Separator brine (location not specified)	The capacity of oysters to clear a turbid medium was significantly decreased at concentrations above 12% in 20-h tests. Longer duration test results indicated that 3% was the threshold level of this clearing effect, that no effect was observed.	Lund 1957, cited in Mackin 1973
Penaeus duorarum pink shrimp juvenile and post-larval	Lab	Behavioural response was observed with salinity increases of 1^{0}/oo	Hughes 1969, cited in Howe 1981
Penaeus setiferus and *P. aztecus* white and brown shrimp, adult and subadult	Lab	Salinity increase of 10^{0}/oo caused increased activity in both species. Avoidance of a brine plume 20^{0}/oo higher than background was observed. Salinity increase of 6.5^{0}/oo did not result in increased activity.	Howe 1981
FISH			
Hypleurochilus geminatus crested blennie	Buccaneer Field Gulf of Mexico	Blennies were apparently attracted to a discharge outlet (concentrations not specified).	Gallaway and Martin 1980, cited in Gallaway 1980
Sciaenops ocellata redfish	Lab	Avoidance responses of salinity plumes 2^{0}/oo above ambient (35^{0}/oo) were not observed. In warm water (25°C), redfish were attracted to brine plumes 1^{0}/oo and 2^{0}/oo above ambient. At colder temperatures (15°C and 20°C), redfish were attracted to warm brine.	Owens *et al.* 1981
redfish	Unknown	Adult and subadults tolerated salinity of 45-50^{0}/oo; however, salinitiy in this range was toxic to embryos and larvae.	Perret *et al.* 1980 and Neff *et al.* 1981, both cited in Owens *et al.* 1981

* Does not include effects attributed to exposure or accumulation of hydrocarbons or trace metals.

CEPEX bag experiments (enclosed bags suspended in the water column) conducted adjacent to the Auk oil field in the North Sea indicated that all components of the zooplankton sampled (Oithona spp. and other copepods) exhibited sublethal effects at a distance of 500-1000 m from the produced water discharge (equivalent to a dilution of 1:700) (Davies et al. 1981).

1.2 Production Field Discharge of Produced Water: Case Studies

In contrast to the relative lack of laboratory bioassay data, the effects of produced water have been examined in several case studies of offshore production areas. Most of the information discussed in the following section is from studies conducted in the Gulf of Mexico. Limited information was also available for the Santa Barbara Channel off California, Mid-Atlantic Outer Continent Shelf and the Beaufort Sea. (See Table 5-3 for the location of oil and gas fields and biological communities examined in each study.) The available case studies which have separately described the effects of produced water on the abundance of organisms and diversity of various biological communities are discussed below prior to review of the effects of individual components of produced water (trace metals, hydrocarbons and salinity).

The most detailed field investigations on the effects of produced water have been completed in the Gulf of Mexico. Gallaway (1980) summarized the results of studies of bacterial, biofouling and benthic communities conducted in the Buccaneer Field. Their bacteriological studies indicated that numerical densities and taxonomic composition were unaffected, but the relative abundance of oil degrading, sulphur-oxidizing and sulphate-reducing bacteria was higher inside than outside the field. Laboratory studies also indicated that produced water inhibited or retarded growth of laboratory cultures, but had no effect on bacteria obtained from the oil field. In the Buccaneer study, produced water was found to significantly reduce the biomass and primary production rates in the biofouling community for a vertical distance of 1 m and a horizontal distance of 10 m from the discharge point. Members of this community included the large Mediterranean barnacle (Balanus tintinnabulum), hydroids, bryozoans, red and green algae, amphipods, copepods, brittle stars, blennies, crabs, pistol shrimp and polychaetes. Increased oxygen consumption by some members of the biofouling community was also measured in the area of the outfall. Examination of the benthic community around the platforms indicated an area of decreased invertebrate abundance within 100 m of the platforms, but the cause of this phenomenon could not be conclusively related to produced water discharge, and the investigators suggested that current eddies around the platform legs were an alternative cause of reduced invertebrate numbers.

TABLE 5-3

SUMMARY OF CASE STUDIES OF THE BIOLOGICAL EFFECTS OF PRODUCED WATER

FIELD OR STUDY AND LOCATIONS	NO. OF PLATFORMS	YRS OF OPERATION/ YRS OF STUDY	ORGANISMS EXAMINED							INVESTIGATED EFFECTS		
			Bacteria	Plankton	Algae	Invertebrates			Fish	Trace Metals	Hydro-carbons	Salinity or other effects
						Benthic Infauna	Benthic Epifauna	Nekton				
Buccaneer - Gulf of Mexico	2-14	15/4	X	X	X	X	X	X	X	X	X	X
Central Gulf of Mexico - Gulf of Mexico	24	25/2				X	X	X	X	X	X	X
South Texas Outer Continental Shelf - Gulf of Mexico	NA	NA/4			X			X	X	X	X	
Trinity Bay - Gulf of Mexico	1					X					X	
OEI Timbalier Bay - Gulf of Mexico	5	40/NA			X	X					X	
Santa Barbara Channel - California	2	15/NA				X	X		X			
Tingmiark - Beaufort Sea	*	1/2					X			X		
Strategic Petroleum Reserve Program - Gulf of Mexico	**			X					X			

* Formation water flow
** Discharge of brine from Bryan Mound
NA Not available

The Ecological Investigation of Petroleum Production Platforms in the Central Gulf of Mexico conducted by the Southwest Research Institute was another major study of the effects of produced water discharges. Bedinger (1981) summarized the results of detailed studies on the microbial community and benthic populations. Overall, the Mississippi River appeared to have a more pronounced effect on microbial activity in the study area than the platform wastes, and a definite increasing trend in microbial activity towards the direction of the river was documented. Microbial activity adjacent to platforms compared to control sites was variable, although oil utilization and microbial activity were higher at platform sites during some sampling periods. No conclusions regarding the effects of platform discharges on benthos could be reached because of two natural environmental episodes (Mississippi River flood and cyclones) which caused significant disruption of the bottom community and masked any possible platform-related effects. The benthic studies indicated a "highly disturbed and unpredictable environment, which results in a stressed community structure" (Bedinger 1981).

Significant effects on biological communities have only been documented when produced water has been discharged into shallow bays or estuaries. For example, Mackin (1971, cited in Mackin 1973) reported that produced water discharges totally destroyed the benthic community within 15 m of the discharges in a shallow (2.4 m) Texas estuary. Some mortality of benthic invertebrates was observed at a distance of 91 m, but a "zone of stimulation" (increased productivity of bacteria, yeasts, fungi, diatoms and other phytoplankton) was found from 122 m to several thousand metres from the discharge. Mackin (1973) also summarized the results of studies conducted by Menzel and Hopkins (1951, 1953) with produced water discharges in five Louisiana bays. Only one bay of the five examined was adversely affected by the discharge. In the Lake Barre Field which was characterized by the largest discharge (950 m^3/d), there was mortality of most of the oysters present in trays that had been positioned 8 m from the outfall. Some mortality of oysters was documented to a distance of 23 m from the discharge, and there was evidence of stunted growth from 23 to 46 m. There was no evidence of any effects of produced water on oysters beyond 46 m. More recent studies in Trinity Bay (Armstrong et al., 1979, cited in Goodman and Troake 1982) indicated that no benthic organisms survived within a 15 m radius of the produced water discharge (at 2-3 m depth). Low benthic biomass extended to a distance of 150 m from the outfall, but no adverse effects were observed at 455 m.

1.2.1 Effects of Trace Metals

Concentrations of trace metals in produced water were discussed earlier in Chapter 2, Section 1.4, and typically exceed background concentrations in sea water by an order of magnitude or more. In addition, several of the metals occurring in produced water are considered to be among those most toxic to marine organisms. In order of decreasing toxicity, these metals are mercury, cadmium, nickel, lead, copper, chromium, arsenic and zinc (Goodman and Troake 1982). In a review of the environmental aspects of produced waters, Koons et al. (1977) cite an increasing body of evidence which indicates that natural processes reduce the activity and toxicities of trace metals dissolved in water, probably due to the binding of trace metals with organic substances. The low toxicity of trace metals in produced water is substantiated by the bioassay studies described previously, which indicate that most organisms tolerate relatively high concentrations of produced water. However, bioaccumulation of metals and subsequent sublethal effects remain areas of potential environmental concern with respect to produced water discharge.

A number of field studies have included examination of trace metal concentrations in marine organisms collected near oil and gas production platforms, although no laboratory studies have apparently been specifically designed to determine bioaccumulation of metals or subsequent sublethal effects resulting from produced water exposure.

Some of these studies (e.g., Tillery 1980; Tillery et al. 1981) report increased levels of trace metals in sediments due to the discharge of produced water, although data on the uptake of trace metals by sessile invertebrates or nektonic organisms are not conclusive (Presley and Booth 1979; Bedinger 1981; Tillery et al. 1981). The existing data neither confirm nor deny the potential for bioaccumulation of trace metals present in produced water. In most cases, background metal concentrations in species being examined, geographical variability in the distribution and abundance of organisms, and variation in metal levels within different age groups of the same population are all inadequately documented. Without these data, statistically sound comparisons are not possible and unequivocal evidence for or against bioaccumulation cannot be obtained. Nevertheless, the potential for bioaccumulation is probably restricted to sessile organisms in the immediate vicinity of produced water discharges. At present, there is also no evidence to suggest that trace metals would be further concentrated in food chains.

1.2.2 Effects of Hydrocarbons

This report section focuses on the effects that have been attributed to oil from produced water, deck drainage or ballast water discharges rather than the extensive literature describing the effects of oil on marine flora and fauna. It should be noted at the outset that produced water discharges and minor spills (<8 m^3) account for an estimated 0.3 percent of the total world-wide input of oil from all sources into the oceans (National Academy of Sciences 1975, cited in Koons et al. 1977). While most investigators agree that the toxic components of crude oil are the water soluble, volatile and aromatic fractions (Bedinger 1981), the relatively low concentrations of these compounds in produced water limit the potential for acute toxic effects. The potential for sublethal physiological or behavioural effects, accumulation of hydrocarbons in tissues of organisms or habitat alteration due to accumulation of hydrocarbons in sediments continue to be areas of concern with respect to oily water discharges.

Laboratory measurements of the effects of oil have been the subject of intensive research. The wide range of experimental conditions, however, and the further extrapolation of these conditions and observed effects to the natural environment, limits the usefulness of this data base. Therefore, the information provided in this section is almost exclusively from the production field case studies summarized in Table 5-3. These investigations are expected to provide the most accurate indication of the effects of chronic, low-level oil discharges, particularly because some of these studies have been completed in areas where oil production has occurred for 25 years or more.

The Central Gulf of Mexico Platform Study (CGS) and the Buccaneer Oil and Gas Field Study are the two most comprehensive field investigations into the cumulative effects of chronic low-level discharge of hydrocarbons in produced water that were available for the present literature review. Each program involved collection of biota and sediments from areas adjacent to drilling or production platforms and also from control areas located outside the production zones. The most significant findings of these two studies were:

Central Gulf of Mexico Platform Study

- Saturated and aromatic hydrocarbons of petrogenic origin were found in low concentrations and in a minority of the 13 fish and 11 invertebrate species collected (Nulton et al. 1981).

- Of 24 platforms examined, a positive correlation between the aromatic hydrocarbon content of sediments and biota was only found at two sites.
- histopathological investigations (Sis et al. 1981) were undertaken to study the possible correlation between chronic low-level hydrocarbon concentrations around production platforms and the condition of fauna in the area. Although there was considerable variability in the data collected for fish species present near different production platforms, the fish with the highest number of histopathological conditions were generally found at locations judged by the authors to be contaminated by hydrocarbons, whereas those individuals with the lowest frequency of abnormalities were collected from the "control" sites.
- Except for Baker et al. (1981) who concluded that benthic fauna of Louisiana continental shelf might be locally affected by petroleum production activities, the general consensus appears to favour the position that there is no consistent correlation between petroleum hydrocarbons in sediments and macroinfaunal community structure, abundance or diversity (Sharp and Appen 1982) or benthic microbial processes (Bedinger 1981).

Buccaneer Oil and Gas Field Study

- Of thirty-one fish species examined by Middleditch (1981), 15 contained petroleum hydrocarbons (alkanes, 1.1-6.8 ppm).
- The fouling mat (barnacle shells and attached organisms) on platforms within about 3 km contained alkanes up to concentrations of 4 ppm, for those organisms living about 3 m from the surface; organisms from depths deeper and shallower than 3 km generally contained no petroleum hydrocarbons.

Several other oil field studies have included examination of hydrocarbon levels in biota but have shown no evidence of petroleum hydrocarbon bioaccumulation. The South Texas Outer Continental Shelf study documented very low levels of total hydrocarbons (<2 ppm), with $C_{15}-C_{17}$ n-alkanes and pristane being the dominant components. The authors suggested that the odd carbon number predominances, the low level of phytane and the absence of aromatics indicated that the area was free of petroleum contamination (Nulton et al. 1981). A review of Gulf of Mexico petroleum effects studies by Nulton et al. (1981) also stated that no evidence of petroleum contamination in biota was found during the MAFLA (Mississippi, Alabama, Florida) OCS investigation. Studies conducted in Santa Barbara Channel off the California coast (McDermott et al. 1978, cited in Rose 1981) also did not indicate elevated petroleum hydrocarbon concentrations in brown rockfish, white-belly rockfish, yellow rock crabs and California mussels, while sixty years of petroleum operations in the Lake Maracaibo Basin have apparently not caused hydrocarbon accumulation in local fish populations (Templeton et al. 1974). In the latter study, Templeton et al. (1974) found the highest hydrocarbon concentrations in the bocachico fish (38.4 µg/g), but the lack of detectable methylnaphthalenes or aromatics suggested that the presence of these hydrocarbons was a result of normal metabolic processes in that species. The Offshore Ecology Investigation also indicated that the "concentrations of all compounds which were in any way related to drilling or production were sufficiently low to present no known persistent biological hazard". The findings of this study, however, have been subsequently qualified by Bender et al. (1979) who suggest that the OEI data were not adequate to eliminate the possibility of subtle cumulative effects resulting from specific hydrocarbon compounds.

In the only available report describing the effects of North Sea hydrocarbon operations, Davies et al. (1981) reported that significant levels of petroleum hydrocarbons in offshore sediments were restricted to areas close to platforms where oil-base drilling muds had been used. The preliminary results of laboratory studies with fish exposed to various concentrations of produced water for 20 to 30 days showed increasing necrosis and decreasing tissue hyperplasia with increasing produced water concentration (Davies et al. 1981).

In summary, most field studies of oily water discharges from petroleum production platforms have been unable to document adverse effects on biota, including accumulation of hydrocarbons in tissues. However, the fact that these studies have not included an examination of sessile infauna is considered a serious deficiency in the existing data base. Several investigators have found increased hydrocarbon concentrations in sediments and therefore, infaunal invertebrates are more likely to be persistently exposed to hydrocarbons (and trace metals) than mobile species that feed in the water column and do not necessarily remain in areas affected by waste discharges. Several authors have examined levels of hydrocarbons in tissues, although only two investigations in the available literature focused on other sublethal effects. Both these studies correlated sublethal effects in fish to contaminants from petroleum production platforms (histopathological conditions, Sis et al. 1981 and AHH activity, Davies et al. 1981). Data obtained from the Buccaneer Field also indicated that habitat (oil platform) faithful fish that feed on fouling organisms contained higher hydrocarbon levels than fish that fed in the water column and were not habitat faithful. Therefore, due to the lack of data for sessile infauna and the results of recent studies of sublethal (histopathological and biochemical) effects, the present authors suggest that further studies may be warranted to document the chronic sublethal effects of hydrocarbons in oily water discharges from production platforms.

1.2.3 Effects Associated with Other Components and Properties of Produced Water

Marine flora and fauna may be affected by several other components and properties of produced water, including its high salinity, temperature and content of organic compounds relative to conditions in the receiving environment, as well as its low dissolved oxygen content. However, all investigators who have studied the effects of produced water agree that rapid dilution and turbulence at the discharge point limit the zone affected by these properties (e.g., Mackin 1973; Gallaway 1980; Bender et al. 1979). Although the distance required before background conditions are reached will vary with the volume of produced water discharged and its particular characteristics, Mackin (1973) suggests that even in comparatively shallow water, background levels of these components may be reached within 2.4 to 15 m.

In his testimony for the Southern California Draft Permit Hearings, Rose (1981) stated that "no investigations of which I am aware have attributed harmful biological effects to those nonconservative properties of the waters" (temperature and dissolved oxygen). In addition, he quoted Turner et al. (1971, cited in Rose 1981) who examined the effects of two production islands in Santa Barbara Channel and found that natural fluctuations in oxygen content dominated those caused by produced water discharge. The Offshore Ecology Investigation in Timbalier Bay also indicated that natural variations in dissolved oxygen, temperature and organic compounds exceeded those resulting from release of produced waters (Bender et al. 1979).

On the basis of this literature, it seems unlikely that any significant adverse effects on flora or fauna would result from the salinity, temperature, dissolved oxygen or total organic content characteristics of produced water.

1.3 Effects of Deck Drainage

Deck drainage may contain a variety of chemicals, including dispersants, solvents, surfactants, refined oil products (e.g., special purpose lubricants and hydraulic oils) and occasionally drilling mud products and completion chemicals. Several different methods for treatment and disposal of deck drainage are currently practised in various oil producing regions. Concentrations of contaminants and discharge volumes vary considerably because of these different disposal and treatment methods. There is little available information on the concentrations of contaminants in deck drainage, with the exception of oil, which generally ranges from less than 25 mg/L to 90 mg/L.

The effects of deck drainage on marine organisms have not been directly examined, primarily because it would not be possible to distinguish effects of deck drainage from effects resulting from other oily water discharges during field investigations. However, information on the acute toxicity of deck drainage components is available from laboratory studies (see Table 5-4). With the exception of fish eggs, larvae and pelagic crustaceans, which all appear to be sensitive to low concentrations of waste oil, most organisms would not be adversely affected by oil concentrations typically present in deck drainage. The recently developed dispersants such as Corexit 9527 are only moderately toxic to most marine organisms (<40 to >1,000 ppm), while detergents are comparatively more toxic (<1 to 58 ppm). Recent laboratory studies of the effects of chemically dispersed oil (Corexit 9527 and Prudhoe Bay crude oil) suggest that relatively low concentrations may be toxic (3.5 ppm) or cause sublethal effects (1.1 ppm) with some marine organisms (Duval et al. 1980). Although the presence of dispersed oil in deck drainage may cause some adverse effects in the immediate area of the discharge, the statements of Hester (1981) and McAuliffe (1981) that the environmental effects of deck drainage are "not detectable" and "not measurable" due to the small volumes discharged, rapid dilution to low concentrations, and short exposure periods for nektonic organisms, are probably a realistic assessment of the overall impact of this waste in offshore areas. The potential for adverse effects may be greater in environments where dilution could be less rapid such as shallow areas with restricted circulation.

TABLE 5-4

ACUTE LETHAL TOXICITY OF SOME TYPICAL COMPONENTS OF DECK DRAINAGE

ORGANISM	MATERIAL	TOXIC CONC. (96h LC50 ppm unless otherwise indicated)	REF.
Rainbow Trout (*Salmo gairdneri*)	Swift's Rig Wash (Detergent)	22	1
Rainbow Trout (*Salmo gairdneri*)	Dominion Rig Wash (Detergent)	14	1
Rainbow Trout (*Salmo gairdneri*)	Amway Rig Wash (detergent)	0.8	1
Rainbow Trout (*Salmo gairdneri*)	V-Wis Rig Wash (Detergent)	58	1
Amphipod (*Gammarus setosus*)	Corexit 9527 (Dispersnt)	175	6
Isopod (*Gnorimosphaeroma oregonensis*)	Corexit 9527 (Dispersant)	>1,000	5
Fourhorn sculpin (*Myoxocephalus quadricornis*)	Corexit 9527 (Dispersant)	>40	6
Hydrozoan (*Tubularia crocca*)	Lubricating oil	24h LC50 25,000	2
Toad fish larva (*Opsanus tau*)	Lubricating oil	25,000 ppm - 80 percent* 50,000 ppm - 100 percent* 100,000 ppm - 80 percent*	2
Atlantic Silverside (*Menida menidia*)	Waste crankcase oil	1,700	3
Unspecified Finfish	Waste oil	1,700	4
Unspecified Finfish	Residual oil	2,000 - 10,000	4
Finfish larvae and eggs	Waste oil	1 - >25	4
Pelagic crustacea	Waste Oil	15 - >50	4

* Percent survival after 50 h exposure.

REFERENCES:

1. Industry/Government Working Group "A" (1976)
2. Chipman and Galtsoff (1949), cited in Craddock (1977)
3. Garner *et al.* (1975), cited in Craddock (1977)
4. U.S. EPA (1975), cited in Craddock (1977)
5. Duval *et al.* (1980)
6. Foy (1979)

1.4 Summary of Important Points

1. Produced water is only slightly toxic (0.1% to 1.0%) to practically non-toxic (>1%) to most marine organisms that have been tested in 96-h laboratory bioassays.

2. Limited toxicity data available for juvenile and larval stages of shrimp and fish suggest that immature individuals may be more sensitive than adults to the effects of produced water.

3. Significant effects on abundance and community structure have only been observed when produced water was discharged into shallow bays (<3 m), and then adverse effects were limited to an area within 100 m of the discharge.

4. There is no clear indication of bioaccumulation of trace metals from produced water in fish or invertebrate species sampled from offshore petroleum production areas..

5. Most field studies of oily water discharge in offshore petroleum production areas have shown no evidence of adverse effects on biota. Some investigators have found a positive correlation between the presence of offshore oil production facilities and (1) increased histopathological conditions, and abnormal enzyme activity in fish, and (2) increased concentrations of petroleum hydrocarbons in fish and invertebrate tissues.

6. Adverse effects of temperature, salinity, dissolved oxygen and organic content of produced water are unlikely due to its rapid dilution in most offshore areas.

7. Deck drainage is typically a small and intermittent discharge, which alone is unlikely to result in any significant adverse effects on marine organisms. It contributes to the overall input of hydrocarbons to the marine environment, however, and may be in part responsible for some of the adverse effects associated with oily water disposal.

8. The potential for dispersed oil and other processing chemical contaminants which enter deck drainage and produced water to bioaccumulate or cause other sublethal effects on marine organims may be greater in shallow areas with poor circulation than in offshore environments where dilution would be rapid. Marine biota most susceptible to adverse effects of these discharges would probably be the sessile invertebrates which colonize production platforms and adjacent benthic sediments, and to a lesser extent, habitat-(oil platform) faithful fish (see section 6.0).

2.0 Drilling Wastes

The level of research into specific types of drilling wastes has varied considerably. For example, the fate and effects of water-base drilling muds have been reviewed exhaustively in articles, conferences and symposia, while there is virtually no available information on the effects of other wastes such as completion, workover and blowout preventer fluids. The following review of water-base drilling fluids has, therefore, been purposely kept to an overview of available information.

Toxicants may be classified by the concentration at which 50 percent of the test organisms die (expressed as an LC50) into categories ranging from practically non-toxic to very toxic (Sprague 1973):

Toxicant Classification	LC50 Value
Practically non-toxic	>10,000 ppm
Slightly toxic	1,000-10,000 ppm
Moderately toxic	100-1,000 ppm
Toxic	1-100 ppm
Very toxic	<1 ppm

2.1 Water-Base Drilling Muds and Cuttings

Literature describing the fate and effects of water-base drilling muds and associated cuttings was recently summarized by Petrazzuolo (1981) and Neff (1982). This information has been used extensively for the present report; it has been supplemented with the results of monitoring programs conducted at several offshore oil exploration or production areas. The latter are considered of greatest overall value in assessing the environmental impacts of drilling wastes.

Drilling fluids tend to differ substantially in their formulation and toxicity, because drilling fluids perform such a large variety of functions in a drilling program. These functions vary from well-to-well and at different depths in the same well. The water depth and oceanographic conditions at different waste discharge sites also greatly affect the dispersion and fate of discharged drilling fluids and formation cuttings. Each of these factors limits the predictive value of both field and laboratory studies into the effects of drilling waste disposal.

The primary environmental concerns associated with the release of drilling wastes in offshore areas are that: (1) either the whole muds or specific components in drilling mud systems may be acutely toxic or result in sublethal responses that are detrimental to sensitive marine species or ecosystems and , (2) metals present in some drilling fluids may be accumulated by marine organisms to concentrations that could be harmful to the organisms or to consumers of fishery products (Neff 1982). The local physical burial of benthic organisms in areas adjacent to drilling waste discharge is a secondary area of environmental concern in most regions.

2.1.1 Toxicity of Drilling Fluid Components

Sprague and Logan (1979) reported that the sum of the toxicities of individual used drilling fluid components was a poor indicator of the acute toxicity of whole mud to freshwater fish. This is probably attributable to physical and chemical changes which occur in a mud system as it is used in drilling programs. Component toxicity data are useful for identifying the most toxic ingredients in different types of muds, particularly when options for alternative additives to mud systems exist (Neff 1982).

2.1.1.1 Acute Toxicity

Data on the acute toxicity of drilling mud components to freshwater fauna are not summarized here, because bioassays with freshwater organisms cannot be extrapolated to marine environments due to differences in the mechanism of toxic action (Neff 1982). Available data on the acute toxicity of specific drilling mud components to marine and estuarine organisms are summarized in Table 5-5. These data indicate that the first three of the four major components of drilling muds (barite, bentonite, lignite) have a low toxicity to most marine species tested. The fourth major component, chrome and ferrochrome lignosulfonates are significantly more toxic, with 96-h LC50 values ranging from 120 to 12,200 ppm for the limited number of invertebrates and fish investigated to date. Plant tannins and sodium phosphate salts are other major constituents of drilling muds that are moderately toxic to marine fauna (Table 5-5).

TABLE 5-5

ACUTE TOXICITY OF DRILLING FLUID COMPONENTS TO ESTUARINE AND MARINE ORGANISMS

(Source: Neff 1982)

COMPOUND	ORGANISM	96-h LC50 (ppm)	REFERENCE
Aquagel^R (Wyoming bentonite)	*Crassostrea virginica*	>7,500	1
	Pandalus hypsinotus	100,000	2
	Acartia tonsa	22,000	3
	Skeletonema costatum	9,600	3
Bentonite	*Crassostrea virginica*	110-119 (192 day LC50)*	4
Barite (Barium sulphate)	several fish and invertebrates	>7,500	1
	M. latipinna	>100,000	5
	Crassostrea virginica	50-60 (216 day LC50)*	4
	Pandalus hypsinotus	>100,000	2
	Acartia tonsa	590	3
	Skeletonema costatum	385-1,650	3
Calcite (calcium carbonate)	*M. latipinna*	>100,000	5
Siderite (iron carbonate)	*M. latipinna*	>100,000	5
Cabonox^R (lignitic material)	several fish and invertebrates	>7,500	1
Lignite	*M. latipinna*	>15,000	6
Chrome-lignosulfonate	*M. latipinna*	12,000	6
Chrome-treated lignosulfonate	*Panaeus setiferus*	465	7
Ferrochrome-lignosulfonate	*Cancer magister*	210 (144-h LC50)	8
	Pandalus danae	120 (144-h LC50)	8

TABLE 5-5 (continued)

ACUTE TOXICITY OF DRILLING FLUID COMPONENTS TO ESTUARINE AND MARINE ORGANISMS

(Source: Neff 1982)

COMPOUND	ORGANISM	96-h LC50 (ppm)	REFERENCE
Iron-lignosulfonate	Penaeus setiferus	2,100	7
Cellulosic calcium carbonate workover additive	Penaeus setiferus	1,925	7
Jelflake^R (shredded cellophane)	several fish and invertebrates	>7,500	1
Impermex^R (pregelatinized starch)	several fish and invertebrates	500-7,500	1
	Crassostrea virginica	3,000	1
Fibertex^R (shredded cane fiber)	several fish and invertebrates	>7,500	1
Mica	several fish and invertebrates	>7,500	1
Low molecular weight polyacrylate	Penaeus setiferus	3,500	7
Quebracho (tannin)	M. latipinna	158	6
Modified hemlock bark extract (tannin)	Penaeus setiferus	265	7
Sodium pyrophosphate ($Na_2H_2P_2O_7$)	M. latipinna	7,100	5
Oilfos^R (Na tetraphosphate)	several fish and invertebrates	>7,500	1
Quadrafos^R (Na polyphosphate)	several fish and invertebrates	500-7,500	1

TABLE 5-5 (continued)

ACUTE TOXICITY OF DRILLING FLUID COMPONENTS TO ESTUARINE AND MARINE ORGANISMS
(Source: Neff 1982)

COMPOUND	ORGANISM	96-h LC50 (ppm)	REFERENCE
Oil well cement	several fish and invertebrates	70-450	1
White lime	several fish and invertebrates	70-450	1
Formaldehyde	Trachinotus carolinus	25-31	9
Dowacide G^R (79 percent (Na pentachlorophenate)	Cyprinodeon variegatus Lagodon rhomboides	0.52 0.066	10 10

* concentrations are given as ppm turbidity which is usually much lower than ppm material added.

M. Mollieniasis

REFERENCES

1. Daugherty (1951)
2. Atlantic Richfield (1978)
3. Shell Oil Co. (1976, cited in Neff 1982)
4. Cabrera (1971)
5. Grantham and Sloan (1975)
6. Hollingsworth and Lockhart (1975)
7. Chesser and McKenzie (1975)
8. Carls and Rice (1980)
9. Birdsong and Avault (1971)
10. Borthwick and Schimmel (1978)

Biocides and surfactants used in drilling mud systems tend to be far more toxic than the major ingredients to marine fauna, although it should be emphasized that biocides are used in very small quantities in drilling mud systems, and are further diluted upon discharge to receiving waters. A large number of studies reviewed by Petrazzuolo (1981) and Neff (1982) indicate that hexavalent chromium salts associated with some mud systems are also moderately toxic or toxic to marine fish and invertebrates, although Neff (1982) emphasizes that the contribution of dissolved chromium to the toxicity of drilling muds is not well documented, largely because most chromium is expected to be tightly bound to lignosulfonate.

2.1.1.2 Chronic and Sublethal Effects

The chronic and sublethal effects of drilling fluid components on marine fauna have not been as extensively examined as acute lethal toxicity. Studies reviewed by Neff (1982) are summarized in Table 5-6, and indicate that pure barite does not have serious effects on planktonic and benthic invertebrates unless present in very high concentrations for extended periods. Nevertheless, Neff (1982) suggests that barite used in drilling mud interacts with, and is partially bound to, the clay-lignosulfonate fraction and may have different effects on marine organisms in the natural environment.

The sublethal effects of chrome and ferrochrome lignosulfonates and virtually all minor additives to drilling mud systems have not been investigated. Studies completed with three biocides found reduced recruitment of benthic invertebrates at very low concentrations of these chemicals.

2.1.2 Toxicity of Used Drilling Fluids

2.1.2.1 Acute Lethal Toxicity

The acute lethal toxicity of used drilling fluids to freshwater organisms has been examined for literally hundreds of mud formulations and species, but fewer investigations have been directed at marine species. Nevertheless, the toxicity of more than 20 used offshore-type drilling fluids has been determined for a range of marine species from the Atlantic and Pacific Oceans, the Gulf of Mexico and Beaufort Sea (see Appendix A).

TABLE 5-6

SUMMARY OF SUBLETHAL AND CHRONIC EFFECTS OF DRILLING MUD COMPONENTS ON MARINE FAUNA

COMPONENT	ORGANISM	OBSERVED EFFECT(S)	REFERENCE
Barite	Planktonic stages of benthic invertebrates	Abundance of meiofauna (Rotifera, Hydrozoa, Turbellaria, Ostracoda, Polychaeta, Bivalvia) unaffected by 10-week exposure to sand:barite mixture, while abundance of nematodes, harpacticoid copepods and copepod nauplii increased.	1
Barite	Benthic invertebrates	Recruitment of molluscs and annelids reduced by 5 mm barite layer on sand, with lesser effect by sand:barite mixtures. Abundance of molluscs and annelids also reduced in sand:barite mixtures	2,3
Barite (500 ppm)	Shrimp	Ingestion of barite by *Palaemonetes pugio* did affect survival, but caused damage to epithelium of posterior midgut. Barite also accumulated in exoskeleton and soft tissues.	4,5
Biocides	Benthic invertebrates	Recruitment of benthic invertebrates to sand substrates adversely affected by extremely low concentrations (10-205 µg/L) of Dowicide and Surflo	6

REFERENCES:

1. Cantelmo *et* al. (1979)
2. Tagatz and Tobia (1978)
3. Tagatz *et al*. (1978)
4. Brannon and Rao (1979)
5. Conklin *et al*. (1980)
6. Tagatz *et al*. (1980)

Neff (1982) suggested that although bioassay methods and conditions have varied considerably, the results of these investigations have been relatively consistent. Most 96-h LC50 values determined for marine organisms have exceeded 10,000 ppm (see Figure 5-1). The sensitivity of many species to drilling fluids has been attributed to an intolerance to high suspended particulate concentrations (Neff 1982). Neff (1982) reports that damage in these intolerant species is caused by mechanical abrasion or physical clogging of delicate respiratory surfaces by fine particulates. In addition, used drilling muds possess some chemical toxicity because the mud aqueous fractions (MAF) and liquid phase (LP) preparations have been shown to be relatively toxic to some species. The physical and chemical toxicities of drilling fluids appear to be additive or somewhat less than additive, with no evidence of synergistic interactions between the physical and chemical toxicities (Neff 1982).

The acute lethal toxicity of water-based drilling muds described in the literature suggests several additional trends which can be summarized as follows:

- The acute toxicity of used drilling muds frequently increases with depth of the well, presumably due to an increase in both the chemical toxicity (minor additives) and physical toxicity (greater weighting) of drilling mud formulations required for progressively deeper formations.

- Spud muds are almost always far less toxic to marine organisms than light-, medium- and high-density lignosulfonate fluids and various seawater-chrome formulations.

- Mortality of some amphipod species appears related to physical alteration of the substrate, with certain species (e.g., Anisogammarus) being less able to support themselves on the sedimented layer of drilling fluid solids.

- Male amphipods appear to be more sensitive to acute toxic effects of drilling fluids than females; this trend has also been observed with other pollutants such as petroleum hydrocarbons.

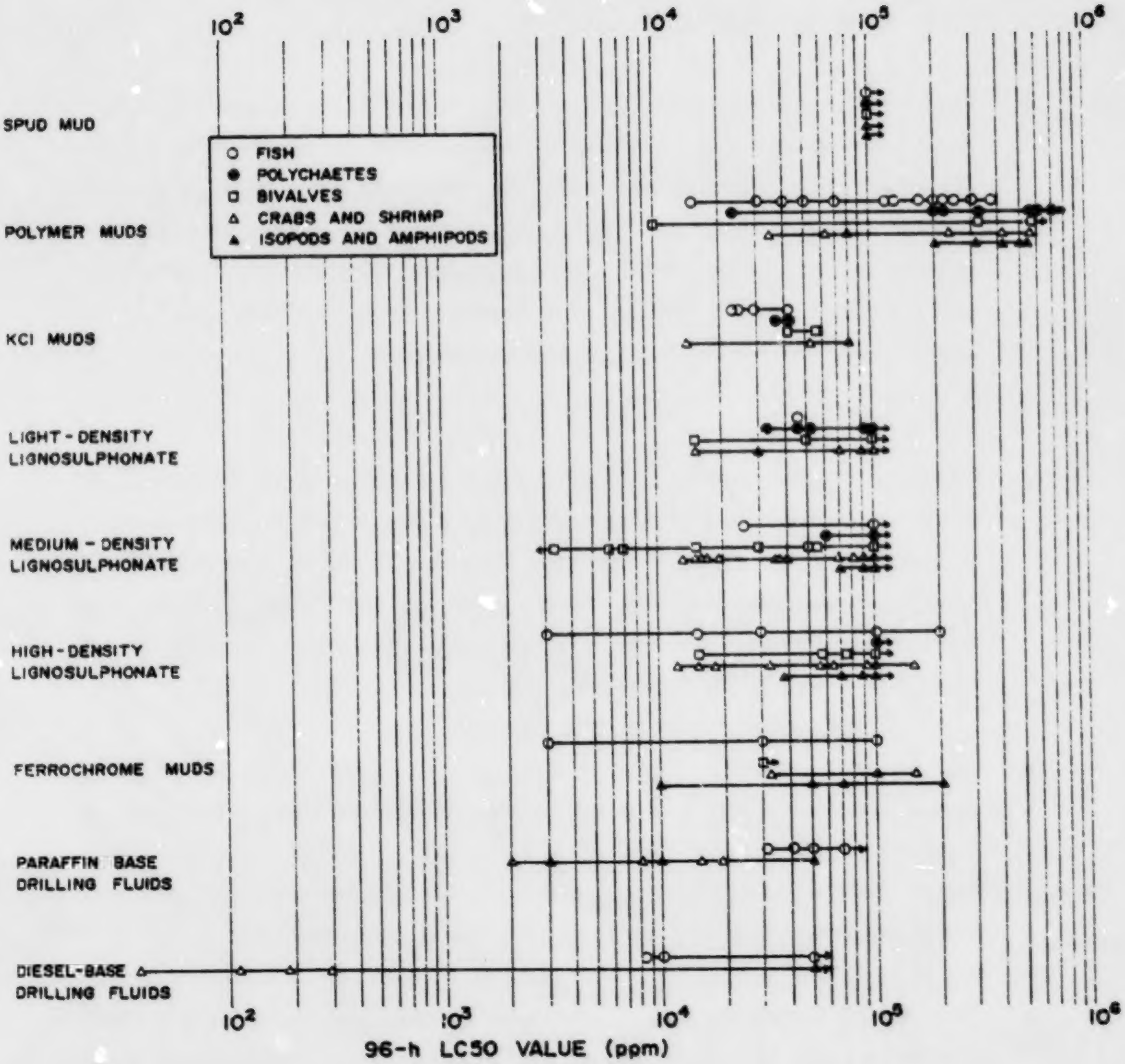

FIGURE 5-1
LETHAL TOXICITY RANGES OF GENERIC DRILLING
MUD TYPES WITH MAJOR GROUPS OF MARINE FAUNA

- Elevated temperatures tend to increase the toxicity of used drilling fluids to shrimp and bivalve molluscs.

- The limited available information suggests that gastropod molluscs are more sensitive to light-density lignosulfonate drilling fluid than to medium- or high-density formulations.

- Studies of shrimp species suggest that: (1) exposure to high concentrations of drilling muds causes damage to the gill epithelia; (2) larvae may be 3-5 times more sensitive than adults; (3) intermoult shrimp are less sensitive than moulting shrimp; (4) in general, the sensitivity of adult shrimp to drilling fluids follow the order LDLF > MDLF > HDLF > SPUD, while zoeal stages are more sensitive to HDLF; and, (5) whole fluids appear to be more toxic than their mud aqueous fractions.

- Seawater-chrome, low- and medium-density lignosulfonate drilling fluids appear more toxic to crabs than high-density lignosulfonate formulations; whole mud or the suspended particulate phase (SPP) appears more toxic than mud aqueous fractions (MAF); and pH adjustment reduced the toxicity of used drilling fluids to Hemigrapsus, indicating a contribution of alkalinity to overall toxicity with at least this species.

- Studies with lobsters (Homarus americanus) suggest that: (1) stage V larvae are more than 20 times more sensitive than adults to the MAF of light-density lignosulfonate drilling fluid; (2) LDLF is more toxic than MDLF; and, (3) increased temperature increases the toxicity of whole muds, but does not affect the toxicity of the aqueous fraction.

- Substantial variability has been found in the sensitivity of different bivalve species to drilling muds, with scallops being considerably more sensitive than clams, mussels or oysters; whole muds and suspended particulate phases (SPP) are more toxic than mud aqueous phases in those species where comparisons have been undertaken.

- In the only echinoderm examined to date (green sea urchin, Strongylocentrotus droebachiensis), light-density lignosulfonate drilling fluids was more toxic than a high-density formulation.

- Trends observed in the acute toxicity of drilling fluids to mysids include: (1) a direct relationship between well depth and the toxicity of XC-polymer drilling fluid to Mysis; (2) a progressive decrease (3-fold) in the sensitivity of the opossum shrimp (Mysidopsis almyra) to the MAF of medium-density lignosulfonate drilling fluid with age from 1-day to 10-day postlarvae; and, (3) a greater toxicity of the suspended particulate phase than the liquid phase of several drilling fluid formulations and Mysidopsis bahia.

- Polychaetes tend to be amongst the most resistant species to acute lethal effects of drilling fluids, with all 96-h LC50 values determined to date exceeding 23,000 ppm.

- Trends observed in the toxicity of drilling fluids to finfish include: (1) a slight increase in the toxicity of several Imco drilling fluids to the Atlantic silversides with aeration, possibly due to differences in dissolved oxygen demand associated with resuspension of particulates; (2) gill epithelia damage in pink salmon (Oncorhynchus gorbuscha exposed to drilling fluids at concentrations greater than 30,000 ppm; (3) a greater toxicity of whole fluids than their aqueous or fine particulate fractions with pink salmon; (4) a greater toxicity of drilling fluids in freshwater than sea water with both rainbow trout (Salmo gairdneri) and coho salmon (O. kisutch); and (5) a reduction in toxicity of drilling fluids with pH reduction in freshwater but not in sea water.

2.1.2.2 Chronic and Sublethal Effects

Petrazzuolo (1981) and Neff (1982) also discuss available information regarding the chronic and sublethal effects of used drilling fluids on marine fauna. The results of these studies are summarized in Table 5-7, and generally indicate that significant sublethal effects are observed at drilling fluid concentrations which are only slightly lower than those which are acutely toxic. On the other hand, chronic exposure of some more sensitive species and life history stages (e.g., juvenile ocean scallops, lobster larvae, mysids and some reef corals) to drilling fluids can result in detrimental effects at concentrations in the 50 to 100 ppm range (Table 5-7). Neff (1982) suggested that damage following prolonged exposure to high suspended particulate concentrations is probably the result of abrasion or clogging of delicate gill and gut epithelial surfaces.

Some of the research which has been conducted on the sublethal effects of drilling fluids is open to criticism. For example, one research team apparently used the survivors of bioassays for test organisms in their sublethal research program, so data resulting from this investigation are of somewhat questionable value. A more serious criticism is the nature of the parameters which have been examined in several studies, particularly those where significant changes during drilling fluid exposure cannot be reasonably related to either detrimental or beneficial responses (e.g., increase and decreases in aspartate aminotransferase or glucose-6-phosphate dehydrogenase enzyme activites), or have limited ecological significance (e.g., short-term changes in oxygen consumption). From the perspective of ecological energetics, the most meaningful sublethal responses are those which can have significant local effects on rates of energy flow and the productivity of populations adjacent to waste disposal sites. For example, elevated rates of excretion and respiration or depressed feeding rates are only likely to be ecologically significant if they eventually decrease the rate of net carbon assimilation and growth of marine populations. Similarly, many of the morphological and histological abnormalities following prolonged exposure to drilling fluids would only be significant if: (1) the organisms remained in areas affected by drilling waste discharge in their natural environment; and, (2) such abnormalities either decreased the chance of survival of affected individuals or increased their susceptibility to predation. For many types of organisms such as the planktonic larvae of benthic invertebrates, zooplankton and most species of fish, exposure of individuals to drilling fluids in the natural environment would either be so local or brief that sublethal responses observed in relatively long-term laboratory

TABLE 5-7

SUMMARY OF CHRONIC AND SUBLETHAL EFFECTS OF USED DRILLING FLUIDS ON MARINE FAUNA

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
DECAPODS		
Mysidopsis almyra	10-30 percent MAF of used seawater-chrome drilling fluid decreased food assimilation and net growth efficiency, resulting in a reduction in growth rate	5
Palaemonetes pugio	Continuous exposure of grass shrimp larvae for the duration of larval development to the MAF of medium and high-density lignosulfonate drilling fluids had no significant effect on development rate at concentrations that were not lethal	4
Pandalus hypsinotus	Exposure to 100,000-150,000 ppm suspensions of whole used high-density lignosulfonate drilling fluids had major histopathological effects on the gills, including necrosis of the respiratory epithelium, hyperplastic changes in certain cell types and debris accumulation within interlammelar areas	8
Carcinus maenus	96-h exposure to MAF of light-density lignosulfonate fluid resulted in progressive increase in G6PdH** enzyme activity in green crab	6
Crangon septemspinosa	96-h exposure to MAF of light-density lignosulfonate fluid decreased G6PdH** enzyme activity in sand shrimp	6
Homarus americanus	3-5 min exposure to seawater suspensions of Mobile Bay drilling mud at concentrations of 10 and 100 ppm interfered with responses to food odours in 29 and 44 percent, respectively, of the chemosensor neurons examined in walking legs of lobsters; layering of mud over the sediment had less pronounced effects	2

TABLE 5-7 (continued)

SUMMARY OF CHRONIC AND SUBLETHAL EFFECTS OF USED DRILLING FLUIDS ON MARINE FAUNA

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
DECAPODS (cont'd)		
Homarus americanus	2 percent MAF of medium-density lignosulfonate fluid increased intermoit duration of larval lobsters by about 3 days	7
Homarus americanus	96-h exposure to MAF of light-density lignosulfonate fluid resulted in progressive increase in AAT* enzyme activity of lobsters at 10 to 100 percent MAF, but a decrease in G6PdH** activity	6
BIVALVES		
Crassostrea virginica	Exposure of oysters to 100 ppm of Mobile Bay drilling mud inhibited rate of regeneration of the shell	1
Crassostrea gigas	Six-week exposure to 5-20 percent MAF of medium and high-density lignosulfonate drilling muds significantly decreased shell growth of oyster spat	4
Mytilus edulis	96-h exposure of mussels to the MAF (30-100 percent) of 3 used chrome lignosulfonate drilling fluids had a tendency to decrease filtration rates and increase respiration and excretion rates; shell growth significantly depressed after 10 days exposure to SSP of low-density lignosulfonate fluid (50 ppm); the 3 fluids also increase AAT* and G6PdH** enzyme activity by 200-250 percent	6

* Aspartate aminotransferase

** Glucose-6-phosphate dehydrogenase

TABLE 5-7 (continued)

SUMMARY OF CHRONIC AND SUBLETHAL EFFECTS OF USED DRILLING FLUIDS ON MARINE FAUNA

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
BIVALVES (cont'd)		
Placopecten magellanicus	Growth rate of the shells of young scallops reduced 19-80 percent by 40 day exposure to SSP of medium-density lignosulfonate fluid (8.9 ppm); smaller scallops more severely affected than larger individuals	7
POLYCHAETES		
Arenicola cristata	33 and 75 percent mortality of lugworms after 1 day exposure to 10 and 100 ppm, respectively, of used Mobile Bay drilling mud	1
Nereis virens	Spud fluid (MAF and whole fluid) had no effect on either AAT* or G6PdH** enzyme activity, while significant progressive decreases in both enzyme activities occurred during exposures to MAF and WF of medium and high-density lignosulfonate fluids	6
ECHINODERMS		
Echinarachnius parma	Sand dollar larvae development was normal during exposure to 100 ppm of Mobile Bay drilling mud; at 1,000 ppm, development was delayed and 70 percent of the plutei were abnormal; sand dollar eggs treated with 1,000 and 10,000 ppm drilling mud had a low fertilization rate, but sperm were unaffected by this treatment	3

* Aspartate aminotransferase

** Glucose-6-phosphate dehydrogenase

TABLE 5-7 (continued)

SUMMARY OF CHRONIC AND SUBLETHAL EFFECTS OF USED DRILLING FLUIDS ON MARINE FAUNA

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
FINFISH		
Fundulus heteroclitus	Early embryonic development of the killifish unaffected by exposure to up to 100 ppm of used Mobile Bay drilling fluid; the rate of development was slowed and completely arrested by exposure to 1,000 and 10,000 ppm, respectively; percent hatching success decreased at 100 ppm and higher mud solids, while heart beat rate slowed by 1,000 and 10,000 ppm mud solids	3
Fundulus heteroclitus	30 percent MAF or greater of used seawater chrome lignosulfonate drilling mud acutely toxic to embryos of killifish, and hatching success decreased at 10 percent or greater MAF; dose-dependent relationship between MAF concentration and development abnormalities; mud-exposed embryos shorter, heavier and had lower heart beat	4
Oncorhynchus gorbuscha	Exposure to 30,000 ppm suspension of whole used high-density lignosulfonate drilling fluid had major histopathological effects on the gills, including necrosis of the respiratory epithelium, hyperplastic changes in certain cell types and debris accumulation within interlamellar areas.	8

* Aspartate aminotransferase
** Glucose-6-phosphate dehydrogenase

REFERENCES

1. Rubinstein et al. (1980)
2. Derby and Atema (1981)
3. Crawford and Gates (1981)
4. Neff et al (1980)
5. Carr et al. (1980)
6. Gerber et al. (1980)
7. Gerber et al. (1981)
8. Houghton et al. (1980)

experiments would be extremely unlikely. On the other hand, benthic infaunal invertebrates and many sessile epifauna could be exposed to drilling fluids for prolonged periods, and some of the effects indicated in Table 5-7 are more probable.

2.1.3 Effects of Drilling Fluids on Benthic Community Development

The effects of drilling fluids and drilling fluid components on benthic community recruitment and development have been examined in several flow-through and in situ investigations summarized by Petrazzuolo (1981) and Neff (1982). Planktonic larvae are the main mechanism of species dispersal and annual recruitment of new fauna to benthic habitats. Studies of this type are therefore useful in assessing the impact of drilling waste. Drilling fluids deposited in, or on, natural substrates may be sufficiently toxic to alter sediment composition so that some species may be prevented from settling, resulting in local progressive changes in community structure.

Some studies indicate that recruitment of annelids and coelenterates on sand substrates is more severely affected by drilling fluids than either arthropods or molluscs (Tagatz et al. 1978, 1980). These studies also suggest that drilling mud concentrations required to affect recruitment are relatively high (sand/mud mixtures of 1:10 and 1:5 or a layer of 2-mm on sand). In contrast, similarly designed studies by Rubinstein et al. (1980) indicated that recruitment of molluscs was most affected by 100 ppm of drilling muds. None of these studies attributed observed differences in recruitment to toxicity of the sedimented drilling mud rather than a change in the texture of the substrate. Investigations conducted in situ by Gilfillian et al. (1981) suggest that physical changes in substrate character may be the most significant factor affecting recruitment. This study concluded that as much as 33 percent of either whole or washed drilling fluid could be incorporated into the sediment with no reduction in population density and only a slight change in community diversity.

2.1.4 Bioavailability of Trace Metals from Drilling Fluids

The results of nine laboratory investigations of the accumulation and release of trace metals from drilling fluids are summarized in Table 5-8. Additional field studies conducted near exploration and production platforms are separately described in Section 2.1.5. The laboratory studies show that some heavy metals associated with

TABLE 5-8

SUMMARY OF LABORATORY STUDIES ON THE BIOACCUMULATION OF TRACE METALS FROM DRILLING FLUIDS

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
DECAPODS		
Paleomonetes pugio	Grass shrimp exposed to 50 mg/L barite in sea water (mostly as solid powder) ingested particulate barite; whole body residues of 9,134 mg/kg barium were observed after 7 days, compared to 26 mg/kg in controls; 106-day exposure to 500 mg/L barite resulted in accumulation in the caparace and hepatopancreas (8,000 ppm), and muscle (1,000 ppm), with molted exuviae casts containing up to 20 g/kg Ba	2
Crangon septemspinosus	96-h exposure of sand shrimp to 50 percent MAF of used low weight lignosulfonate drilling fluid resulted in Cr accumulation to about 2 ppm, but nearly all released during subsequent 96-h exposure to clean sea water	4
Portanus spinicarpus Paneus aztecus Palaemonetes pugio	Exposure of 3 crustaceans to used sea water chrome lignosulfonate drilling mud resulted in Cr accumulation, but Cr rapidly released when organisms returned to mud-free sea water	5
AMPHIPODS		
Onisimus sp. Boeckosimus sp.	20-day exposure to XC-polymer drilling fluid resulted in maximum metal accumulation of 1.7 ppm Cd (control = 0.3 ppm), 5.3 ppm Cr (control = 3.0 ppm), 20 ppm Pb (control = 9.7 ppm) and 140 ppm Zn (control = 85.8 ppm)	8
BIVALVES		
Mercenaria mercenaria	Hard shell clams exposed to a 1.5 mm layer of barite for 10 days, but no statistically significant accumulation of Zn, Hg, Cr, Pb, Cd, Cu and Ba observed, despite a slight increase in Cu concentrations in the overlying water	1

TABLE 5-8 (continued)

SUMMARY OF LABORATORY STUDIES ON THE BIOACCUMULATION OF TRACE METALS FROM DRILLING FLUIDS

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
BIVALVES (cont'd)		
Placopecten magellanicus	Scallops exposed for 27 days to 1 g/L of used low-density chrome lignosulfonate drilling mud, and Cr concentrations in kidney increased to nearly 3 ppm compared to 1.5 ppm in controls (no accumulation in adductor muscle); scallops exposed to 1 g/L of synthethic attapulgite clay based mud for 28 days resulted in accumulation of up to 100 ppm Ba in kidney (control = 12 ppm)	3
Placopecten magellanicus	Scallops exposed to the SPP of a medium-density lignosulfonate drilling mud for 40 days contained about twice as much Cr as control organisms, while exposure to the MAF for 7 days resulted in a maximum of about 3 times control Cr concentrations; scallops accumulated more Cr more rapidly from a 2 percent MAF than from a 8.6 mg/L SPP, which both contained the same Cr concentration in the aqueous phase	9
Mytilus edulis	Mussels accumulated approx. 2-4 ppm Cr in tissues during continuous exposure for 30 days to SPP of used light-density lignosulfonate mud containing 0.03 ppm Cr, but did not accumulate Cd from medium-density lignosulfonate mud and seawater chrome lignosulfonate mud; mussels also exposed to several forms of chromium for 7 days--Cr in the MAF of used medium-density lignosulfonate mud was the form least available, with Cr as inorganic trivalent salt ($CrCl_3$) most readily accumulated, followed by Cr associated with ferrochrome lignosulfonate	4

TABLE 5-8 (continued)

SUMMARY OF LABORATORY STUDIES ON THE BIOACCUMULATION OF TRACE METALS FROM DRILLING FLUIDS

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
BIVALVES (cont'd)		
Rangia cuneata	Clams accumulated significant amounts of Cr when exposed to sand substrate containing a layer of seawater chrome lignosulfonate drilling fluid; most Cr released within 24 h when clams returned to clean substrate; clams also accumulated Cr from the MAF of this drilling fluid	5
Rangia cuneata	Marsh clams accumulated only small amounts of Cr and Pb from the MAF of medium-density lignosulfonate drilling fluid; less than half of Cr released in 4 days when clams returned to clean sea water	6
Crassostrea gigas	Juvenile Pacific oysters exposed to MAF of 3 drilling muds for 2 weeks showed little or no net accumulation of Cr, Pb or Zn; maximum Cr accumulated (7.53 ppm, 3 times control) was during exposure to 40 percent MAF of medium-density lignosulfonate mud; oysters exposed to 40 percent MAF of this mud also accumulated slightly more than 2 ppm Pb in 14 days, but there was no Zn accumulation from the MAF of any mud	
Crassostrea virginica	100-day exposure of oysters to concentrations of 10 to 100 ppm of Mobile Bay (Alabama) drilling muds resulted in accumulation of Ba, Cr and Pb; maximum metal concentrations in oysters exposed to 100 ppm drilling mud were 56.17 ppm barium (control = 1.90 ppm), 9.98 ppm Cr (control = 0.65 ppm) and 3.26 ppm Pb (control = 1.08 ppm); Al, Zn and Fe were not accumulated	

TABLE 5-8 (continued)

SUMMARY OF LABORATORY STUDIES ON THE BIOACCUMULATION OF TRACE METALS FROM DRILLING FLUIDS

TAXON/ORGANISM	EXPOSURE CONDITIONS AND OBSERVED EFFECTS	REF.
POLYCHAETES		
Nereis virens	Nereis exposed to a 1.5 mm layer of barite for 10 days, but no statistically significant accumulation of Zn, Hg, Cr, Pb, Cd, Cu and Ba observed, despite slight increase in Cu concentrations in overlying waters; a slight rise in Cu and Ba concentrations in polychaetes was not statistically significant	1
Nereis virens	No accumulation of Cr by sand worms following 96-h exposure to MAF or LSP preparations of high-density lignosulfonate drilling fluid	4
Nereis virens	Cr accumulation observed during exposure to used seawater chrome lignosulfonate drilling fluid; Cr released more slowly after transfer to clean sea water than observed with clams	5

REFERENCES

1. Espey, Huston and Associates (1981)
2. Brannon and Rao (1979)
3. Liss et al. (1980)
4. Page et al. (1980)
5. Carr et al. (1981)
6. McCulloch et al. (1980)
7. Rubinstein et al. (1980)
8. Tornberg et al. (1980)
9. Gerber et al. (1981)

drilling fluids have a limited bioavailability to marine fauna, with chromium being the most readily accumulated metal from drilling muds. Neff (1982) suggests, however, that available information indicates that "there is little likelihood that heavy metals would be accumulated from environmentally realistic levels of used drilling fluids in edible portions of shell and finfish to concentrations that would pose a health hazard to users of such fishery products".

2.1.5 Exploration and Production Field Case Histories

Several large-scale investigations or monitoring programs have been conducted in areas adjacent to offshore drilling waste disposal, and these studies provide the most reliable information on the fate and effects of drilling fluids and associated formation cuttings.

(a) Lower Cook Inlet (Alaska) C.O.S.T. Exploration Well Studies (C.O.S.T. = Continental Offshore Stratigraphic Test).

Underwater television examination of the seafloor (60-65 m depth) at the C.O.S.T. well site showed no visible accumulation of cuttings; the maximum accumulation of cuttings in any benthic sediment sample was 3 percent by weight. Barium concentrations in benthic samples were also within the background limits determined before the drilling program.

The benthic community in the immediate vicinity of the drilling vessel was found to be typical of that found on dynamic sandy bottoms subjected to frequent physical disturbance in the form of moving sand waves. Numbers of organisms, numbers of species and species diversity at stations within 200 m of the drilling vessel were not significantly different before and after the drilling program, although the authors indicated that statistical comparison of predrilling and postdrilling data was complicated by an incomplete knowledge of normal seasonal cycles in the area and by sampling anomalies. It was concluded that rates of accumulation of cuttings and drilling mud on the bottom did not noticeably alter the character of the benthic community.

Dye studies conducted during the exploration program indicated a rapid dilution (10,000:1) of the drilling effluent within 100 m of the discharge site. The concurrent mathematical modelling results showed that even for the maximum bulk mud discharges, the total suspended solids (TSS) at 100 m would be only 6 mg/L, whereas naturally occurring TSS values for the C.O.S.T. well site ranged from 2 to 20 mg/L. The investigators compared these levels with the TSS level (1,100 mg/L) of a 0.3 percent whole mud solution which represented the lowest LC50 value established, and suggested that this concentration was about nine times the concentration of suspended solids in the normal drilling discharge at the point of discharge. Dames and Moore (1978) also reported no mortality among test salmon fry, shrimp and hermit crabs held for four days in live boxes at 100 and 200 m distances from the drilling vessel. There was no significant uptake of heavy metals by pink salmon fry held at a location 100 m from the drilling vessel.

(b) Tanner Bank (California) Mud and Cuttings Study

Tanner Bank is a rock reef located in 60 m of water approximately 160 km offshore from Los Angeles, California, and had been designated as a "unique biological area" by the Pacific Outer Continental Shelf Office of the Bureau of Land Management before initiation of drilling operations in late 1976. The distribution and abundance of the colonial hydrocoral Allopora californica was the principal concern in the formation of this regulatory policy.

Water quality investigations indicated that the discharge of drilling mud and cuttings caused minor and transient modifications to the receiving waters. Water pH, temperature, salinity and dissolved oxygen content were not affected beyond 30 m of the discharge pipe, while background trace metal and suspended solids concentrations were reached within 200 m of the drilling platform. In a similar manner, sedimentation studies indicated that measurable amounts of discharged materials settled to the ocean bottom up to 120 m from the discharge source, but there was no evidence of elevated sedimentation at a distance of 915 m downcurrent from the operation. Ecomar (1978) reported that "the mud and cuttings dilution and dispersion was so complete that residual materials were visually undetectable on the rock reef or directly below the discharge site".

A submersible was used to identify reef-associated biota and assess the effects of the drilling operations on Tanner Bank. The biological reconnaissance encompassed a more than 100,000 m^2 area covering six linear km from the discharge site. The investigators were able to record marked depth-related zones in the abundance and diversity of benthic flora and fauna, but concluded that drilling operations at Tanner Bank had no significant observable adverse effect on the associated reef community.

(c) Reindeer Island (Beaufort Sea) Stratigraphic Test Well Studies

NORTEC (1981) reported statistically significant differences between deep water and shallow water sites in their study area in terms of infaunal abundance, diversity, species richness, evenness and biomass, while temporal differences in faunal abundance were identified in both the control and disposal sites. As with the Lower Cook Inlet C.O.S.T. well studies, incomplete knowledge regarding natural seasonal fluctuations in benthic community structure and faunal abundance hampered determination of any significant seasonal trends. Nevertheless, based on available data, there was no indication of change in the benthic fauna attributable to either the above-ice or below-ice disposal of drilling fluids. Trace metal analyses conducted during this study indicate that heavy metal concentrations in organisms subjected to both short-term (96-h) and long-term (up to 1 year) exposures to drilling effluents were generally within the range of natural variability of these metals in unexposed organisms. *In situ* exposure to discharged drilling fluids also had no apparent effect on species of clams (*Astarte* spp. and *Liocyma fluctuosa*) used in live-box experiments.

Above-ice disposal of drilling fluid had no effect on the diatom assemblages that developed during the subsequent summer. NORTEC (1981) report that samples collected three months after the introduction of effluents to the water column showed no significant differences in abundance, species diversity and evenness values between the control and waste disposal areas. The abundance of infaunal invertebrates, however, was lower at the above-ice disposal site than at the control site during all sampling periods. The investigators indicated that only numbers of polychaetes and harpacticoid copepods were significantly lower at the disposal site. They also suggested that reduced abundances at the disposal site may have been attributed to natural variations in ambient physical conditions (sediment grain size) at the two sites, because trace metal analyses of bottom sediments and benthic organisms indicated that drilling effluents did not remain at the disposal site. NORTEC (1981) also reported that modelling of below-ice discharge and *in situ* tests indicated that concentrations of drilling effluents at the seafloor were 25 percent or less of the lowest 96-h LC50 value determined in their concurrent laboratory bioassays.

(d) Mid-Atlantic Outer Continent Shelf Exploration Program

The objective of the Mid-Atlantic OCS Monitoring Program was to determine the effect of drilling discharges on ambient water quality, bottom sediments and the benthic community. The study involved monitoring of the environment around the well site before the rig moved on location, while the drilling operations were occurring, and after the rig moved off location (Ayers et al. 1980).

Drilling discharges caused some local changes in grain size distribution and clay minerology of the surface sediments, as well as changes in the trace metal content of the sediments and benthic organisms. Brittle stars, molluscs and polychaetes that were collected during the post-drilling survey had significantly higher barium and mercury content than those collected before initiation of the drilling program (Mariani et al. 1980). In addition, chromium and lead were concentrated to levels higher than those found in sediments by at least one of the three major taxa in the region (Cr in polychaetes and Pb in brittle stars). Increased concentrations of lead and barium in invertebrate tissue were reported within 16 km and 3.2 km of the well site, respectively, but barium accumulation was most evident within the immediate vicinity of the well. No simple correlations between metal concentrations in sediment and tissue samples were found, although concentrations of barium in tissue samples were typically an order of magnitude higher than those observed in the sediment.

Additional effects of drilling waste discharge on the benthic community were described by Menzie et al. (1980). These effects included: (1) increased abundance of fish (primarily hake, Urophycis spp.) and crabs (primarily Cancer borealis) in the immediate vicinity and to the south of the well site in the post-drilling survey, possibly due to attraction by the increased microrelief associated with cuttings accumulations; (2) accumulations of mussels (Mytilus edulis) that had fallen from the drilling rig and anchor chains; (3) burial of sessile fauna within approximately 150 m of the well; and, (4) reductions in the abundance of macrobenthos beyond the immediate vicinity of the well. The latter effect may have been in part due to increased predation by fish and crabs, as well as the increased clay content of the sediments. Menzie et al. (1980) report that reductions in the abundance of benthic invertebrates could be detected up to 800 m from the well site.

(e) Netserk F-40 Artificial Island, Beaufort Sea

Crippen et al. (1980) described the physical, chemical and biological effects of the drilling of a shallow-water exploration well in the Beaufort Sea. Elevated levels of Hg, Pb, Zn, Cd, As, and Cr were found in the sediments at one or more stations in the vicinity of the discharge site, particularly within a 45 m radius of the artificial island. The density and biomass of benthic invertebrates were also reduced in the immediate vicinity of the site, although no correlation was evident between metal levels in the sediment and concentrations within infauna. Density and biomass values for benthic fauna were reduced within 300 m of the island, but were equivalent to background levels where distances were 300 m and greater. The authors report that the only possible presence of bioaccumulation was that of mercury at two stations near the discharge site. Crippen et al. (1980) also suggested that smothering and modification of the natural marine sediments by the borrow material during construction of the artificial island probably had a greater impact on the marine environment than did drilling waste disposal.

(f) Ecological Investigations of Petroleum Production Platforms in the Central Gulf of Mexico

This study was designed to avoid sites where actual drilling influenced the environment, although data collected at several of the platforms provided evidence regarding the cumulative long-term effects of drilling waste discharge. Baker et al. (1981) summarized the results of several other investigations into the effects of drilling waste disposal on benthic communities of the Gulf of Mexico. The reports from some of these investigations could not be obtained for the present literature review, and therefore, a portion of the review of these authors is repeated below.

> "Ray and Shinn (1975) determined theoretically that for a current of 0.5 ft/sec and a discharge rate of 40 and 250 barrels per hour, dilutions of 1,000:1 would be expected at approximately 1,000 and 10,000 ft. This dilution not only reduces turbidity but also dilutes any toxicants within the drilling fluid. The finer materials are driven away by the current and the larger hole cuttings form a pile under the platform. In areas of low current speed, such as the Gulf of Mexico, piles up to 30 m in diameter and 1 m in height have formed from surface discharges (Zingula, 1975; Zingula and Larsen, 1977; Gettleson, 1980). When cuttings are shunted to within 10 m of the bottom, the pile height is 2 to 3 m, but its radius is only 9 to 11 m

> (Continental Shelf Associates, 1975; Miller, 1976). Tropical cyclones and natural weathering, through settling, compaction, and current dispersion, combine to scatter this accumulation, so that the sediment underneath the platform appears to be similar to the surrounding environment within a very short time (Gettleson, 1980). Thus, any 'burial effect' is localized, probably to within 300 m of the platform, and the fauna probably recovers soon after disposal of drilling fluid ceases (Shinn, 1974; George, 1975; Zingula, 1975; Gray *et al.*, 1980).
>
> Zingula (1975), Zingula and Larsen (1977) and Gettleson (1980) have discussed the effect of accumulation of drill cuttings on the benthos. Rapid accumulation probably smothers the less mobile benthic organisms, with the extent of the effect depending on the mobility and size of the organisms relative to the depth of accumulation. Examinations of piles of cuttings have shown them to be relatively nontoxic as the piles are quickly colonized by a variety of organisms (George, 1975; Zingula, 1975; Zingula and Larsen, 1977). Many of these organisms are capable of living only on hard substrates and therefore may be new.
>
> Gettleson (1980) reported that benthic samples collected before drilling operations in the MAFLA OCS contained a significantly greater number of meiofauna individuals than samples collected during and after drilling. Greatest decreases in the number of individuals were noted at 100 m from the platform, but reduced populations extended to 1,000 meters. There was partial recovery of the populations three months after drilling was completed. Holland (1977) in the BLM South Texas OCS found a decrease in the number of species and individuals between pre- and post-drilling samples taken at the actual drill site, but found no noticeable changes in populations at distances of 100 m and greater".

The Southwest Research Institute (1981) studies on the Louisiana OCS did not involve collection of benthos samples from stations within 500 m of any production platforms. The authors suggest therefore that, based on the results of the above studies, there should have been no burial effects of drilling fluids or cuttings at that distance. However, significant negative correlations were observed between chromium concentrations in the sediments and the number of meiofaunal species and total abundance of macroinfauna, as well as the abundance of Chromadoridae, *Tharyx marioni* and *Nereis*. Baker *et al.* (1981) report that these significant correlations with chromium may relate to the use of chromium-treated lignosulfonate drilling muds. They also suggest that chromium probably remains bound in fine-grained sediments characteristic of the Louisiana OCS, and is therefore not available for biological uptake.

2.1.6 Summary of Effects of Water-Base Muds and Cuttings

1. The components that comprise the largest proportion of drilling fluids (barite and bentonite) are practically non-toxic.

2. Some minor constituents of drilling fluids (e.g., biocides) are moderately to very toxic, but are present in very low concentrations in the whole mud.

3. Whole muds, as a rule, are less toxic than the individual components, due to neutralization reactions between components and adsorption of soluble components on clay particles in the drilling fluid.

4. The most common drilling mud systems used in exploratory and production drilling in North America have been low-, medium- and high-density clay-chrome lignosulfonate systems which range from slightly toxic to practically non-toxic for most organisms tested.

5. The acute toxicity of drilling fluids has been examined within a range of phyla and classes of marine organisms, including several life history stages, and these studies indicate that 96-h LC50 values typically range from 1 to 10 percent, with most falling in the 3 to 7 percent range.

6. Susceptibility of marine flora and fauna varies with phylum, class and stage of development, although 96-h LC50 values normally do not vary more than one to two orders of magnitude for the same mud system.

7. Much of the toxicity of the mud aqueous fraction of drilling fluids appears to be attributable to volatile organic components, which may include petroleum hydrocarbons and byproducts of lignosulfonate and lignite, whereas suspended solids may cause mortality in sensitive species and life stages by clogging and damaging gill epithelia.

8. Sublethal and chronic effects of drilling fluids have only been observed at concentrations approaching those which are acutely toxic.

9. Changes in the texture of the bottom sediments near drilling mud discharge sites may affect local benthic community structure by reducing recruitment by the planktonic larvae of polychaetes, molluscs and coelenterates.

10. Laboratory studies indicate the barium, chromium, cadmium, zinc and lead present in drilling muds may be accumulated in the tissues of some species of marine fauna, with chromium being the most readily accumulated heavy metal; however, these metals have also been shown to be depurated relatively quickly when organisms are no longer exposed to drilling fluids.

11. The biological effects of drilling mud and formation cutting discharge in offshore exploration and production areas examined to date have been highly dependent on the oceanographic character of the receiving environment, particularly water circulation and substrate composition.

12. Offshore drilling waste disposal affects benthic infauna to a greater degree than other marine organisms, but most studies suggest that impacts are restricted to an area within 300-500 m of discharge sites.

13. Documented impacts of drilling waste disposal have included burial of sessile fauna; reduced abundance or changes in the species composition of benthic fauna; attraction of epifauna and fish to cuttings piles; and, accumulation of barium, chromium, lead and mercury in the tissues of some species of fauna in some areas.

14. Concentrations of trace metals measured in the tissues of benthic invertebrates do not correlate well with metal levels measured in sediments near discharge sites, probably because most metals associated with drilling muds are organically bound or adsorbed to particles and have limited bioavailability.

2.2 Oil-Base Muds and Oily Formation Cuttings

Information on the biological effects of oil-base drilling muds is limited, presumably due to (1) their high cost and limited use in drilling applications in offshore North American waters, and (2) regulations prohibiting the discharge of these fluids in both Canadian and U.S. waters. With the recent development of mineral-oil-base muds (rather than diesel oil), however, these specialized mud systems may be used more often in the future. Where the proprietary information is available, it appears that most low-toxicity oil-base muds use the same or similar formulations to Exxon's Mentor^R 28 oil. These types of products are highly refined, low viscosity, paraffinic-base mineral-seal-oils.

2.2.1 Laboratory Studies

Available information on acute lethal toxicity of mineral oil-base muds originates primarily from the United States. Bioassay data from the United Kingdom were not available for this review. Toxicity information for a variety of standard fish and crustacean test species indicate that the substitution of a mineral oil for diesel oil in mud formulations reduces lethal toxicity in suspended particulate phase tests by factors of from 3 to 263 (Table 5-9). Liquid phases of diesel-oil-base muds are much less toxic than the suspended particulate phases, probably because of the removal of most oil in particulate (>45 µm) form during the preparation of the liquid phase media (method in EPA/COI 1977). Crustaceans are, as a rule, more sensitive than fish to the oil-base muds.

Most of the toxicity data presented in Table 5-9 represent tests on warmer-water species for Gulf of Mexico drilling applications. Test temperatures of 23-25°C are therefore substantially greater than mean temperatures in Canadian water where oil and gas development is likely to occur. The competing factors of decreased hydrocarbon volatilization rates from test solutions and slower biological rate processes will probably alter toxicities relative to the values determined at higher temperatures. See Figure 5.1, page 5-25 for comparison of the toxicity of diesel-base and paraffin-base oil muds to water-base muds.

TABLE 5-9

THE ACUTE LETHAL TOXICITY OF MINERAL OIL AND DIESEL OIL-BASE DRILLING MUDS TO MARINE ORGANISMS

TEST ORGANISM	MUD TYPE	PREPARATION TYPE	TEST TEMP. °C	96-h LC50 (ppm)	MANUFACTURER SOURCE
FISH:					
Menidia menidia (silverside)	Vertifaze with mineral oil	SPP	25	>30,000	Magcobar
	Vertifaze with diesel oil	SPP	25	>10,000	Magcobar
	Drillfaze with DOS-3 (mineral)	SPP	25	>30,000	Magcobar
	Oilfaze	SPP	25	>30,000	Magcobar
	Vertion	SPP	25	>30,000	Magcobar
	Carbo-S.E.A. (mineral)	SPP	23	>50,000	Milchem
		LP	23	>40,000	Milchem
M. beryllina (silverside)	Invermul NTX (mineral)	SPP	22	>50,000	Baroid
		LP	22	>50,000	Baroid
	Invermul (diesel oil)	SPP	22	8,400	Baroid
		LP	22	>50,000	Baroid
Cyprinodon variegatus (sheepshead minnow)	Clean-spot (mineral)	SPP		>50% MORT in 100,000	Chromalloy
Lagodon rhomboides (pinfish)	Clean-spot (mineral)	SPP		>70,000	Chromalloy
CRUSTACEANS:					
Crangon crangon (shrimp)	Drillfaze D/O (diesel) (North Sea)	SPP	15	34	Magcobar
	Drillfaze 1 & 2 (North Sea) (mineral)	SPP	15	>10,000	Magcobar
Penaeus aztecus (brown shrimp)	Clean-spot (mineral)	SPP		19,000	Chromalloy
Palaemonetes pugio (grass shrimp)	Clean-spot (mineral)	SPP		15,000	Chromalloy
	Invermul NTX (mineral)	SPP	22	>50,000	Baroid
		LP	22	>50,000	Baroid
	Invermul (diesel)	SPP	22	290	Baroid
		LP	22	>50,000	Baroid
Mysidopsis bahia (mysid shrimp)	Clean-spot (mineral)	SPP		18,000	Chromalloy
Mysidopsis bahia	Low aromatic (< 0.1 %) (paraffin)	MAF	-	90% survival in 96 h	-
M. almyra (mysid shrimp)	Carbo-S.E.A. (mineral)	SPP	23	10,000	Milchem
		LP	23	8,000	Milchem
MOLLUSCS:					
Mercenaria mercenaria (hard shell clam)	Carbo-S.E.A. (mineral)	SP	23	98% survival in 96 h	Milchem
	Invermul NTX (mineral)	SP	22	90% survival in 96 h	Baroid
	Invermul (diesel)	SP	22	82% survival in 96 h	Baroid

2.2.2 Field Investigations

Residual oil from oil-base drilling fluids present on discharged cuttings continues to be of prime biological concern because the drilling muds themselves are not released to the marine environment. Studies conducted in the North Sea indicate that considerable quantities of oil remain with the cuttings after they have been cleaned. Diesel oil-base drilling muds have been used for production drilling in the North Sea, and several contacts made during the present investigation indicate that monitoring programs have been initiated in conjunction with these operations. However, the results of these investigations were not released in time for inclusion in this literature review.

The chemical impacts of the disposal of diesel-wet cuttings have been under investigation by British and Norwegian research teams (Grahl-Nielson et al. 1980; Davies et al. 1981). Studies conducted at the Statfjord A platform in the North Sea indicate that approximately 300 m^3 (250 tons) of oil were discharged with 1,250 m^3 of drill cuttings (Grahl-Nielson et al. 1980). These authors report that hydrocarbons resulting from the discharges were detected in the sediments over an area of 5 km^2, and exceeded 1,000 ppm in the vicinity of the production platform. The results of the biological investigations have not been published but, it is probable that significant mortality and uptake of hydrocarbons by benthic infauna will be associated with this operation. Monitoring programs initiated in Forties, Brent and Beryl fields also indicate that much higher sediment oil levels in the latter field may be associated with the use of oil-base drilling muds (Davies et al. 1981). Surveys conducted in these production fields have shown that the concentrations of 2-3 ring aromatics at stations within 1.6 km of the Beryl production platform are two orders of magnitude higher than at stations further from the platform. Analyses of the produced oil and of the oil-base mud used at Beryl, suggest that the contamination is from oil-wet cuttings discharges.

A picture of benthic contamination from oily cuttings discharges in North Sea fields where oil-base mud systems are used is emerging. Inner areas within 100 m of the platform may have patches of abiotic sediment, with severe oil contamination (1000 µg/g oil) and macrofauna dominated by large numbers of a few opportunistic species. Within 1.6 km, oil concentrations occur up to 200 µg/g; a general decrease in species diversity is found as the platform is approached.

2.3 Well Completion and Workover Fluids

Completion fluids may include solutions of zinc bromide, calcium bromide, calcium chloride and a range of additives such as surfactants and viscosifiers as well as acids such as hydrochloric and hydrofluoric.

Completion and workover fluids usually contain hydrocarbons, because they are treated and discharged in the same waste stream as any formation water. The remaining environmental concerns associated with the discharge of these fluids are the elevated levels of dissolved zinc (when $ZnBr_2$ is used) and possibly organobromides formed by the complexing of bromide with the relatively large quantities of organic carbon found in produced waters. The potential toxicity of some additives to completion and workover fluids, as well as the effects of reduced water pH, are of lesser environmental concern, because surfactants and other additives are present in low concentrations. These solutions are only slightly acidic after their residence in geological formations and dilution with formation water.

The acute lethal and sublethal effects of completion and workover fluids do not appear to have been directly investigated in relation to offshore hydrocarbon production, although the presence of elevated dissolved zinc and bromide levels in these fluids could result in local effects on marine flora and fauna. The zone of influence of these ions, however, would be extremely small and potential impacts limited to the short periods when a well is in initial production (for completion fluids) or immediately following a workover (for acidizing fluids). There is an extensive literature describing the effects of zinc on aquatic organisms, but the biological effects of bromides and organobromides on marine flora and fauna are very poorly documented. The bromide ion is not expected to be of significant concern in marine environments because it occurs naturally in sea water at relatively high concentrations (4-7 ppm) (Lyman and Fleming 1940; Riley and Chester 1957, both cited in Parsons and Takahashi 1973). On the other hand, organohalogens are definitely an environmental concern.

Zinc is an essential element at trace levels, and is naturally present in sea water at concentrations from 0.01 - 2.01 µg/L (Bruland et al. 1978). As with most trace metals, most studies on the toxicity of zinc have been conducted with freshwater organisms. The toxic form of zinc is Zn^{2+} (Taylor and Demayo 1980), and this is also the predominant dissolved species in sea water and completion fluid formulations containing $ZnBr_2$. Taylor and Demayo (1980) report that the mechanism of zinc toxicity appears to be an interference with normal gaseous exchange processes.

The limited number of studies completed with marine organisms indicate that acute lethal concentrations of dissolved zinc (0.1-200 ppm) are at least an order of magnitude higher than the upper range of background levels in sea water. Adverse sublethal effects of zinc from completion fluids, as with acute lethal effects, would be local and short-term.

The effects of bromide ion and organobromides on marine flora and fauna have been the subject of limited investigation. It is considered possible that most bromide associated with completion fluids will be complexed with organic compounds present in formation water, because the rapid substitution of bromine for chlorine in chlorinated organic compounds has been reported by several authors (e.g., MaClady et al. 1977, Sugam and Helz 1977, both cited in Erickson and Hawkins 1980). Erickson and Hawkins (1977) examined the effects of several organobromides on the uptake of ^{14}C by estuarine phytoplankton, and found no statistically significant effects with bromoform, 4-bromophenol and ethylene bromide at concentrations of 2 ppm. The same concentrations of 2,4,6-tribromophenol and pentabromophenol, however, resulted in 11 and >90 percent inhibition of photosynthesis in algal species tested.

The acute toxic effects of sodium bromide on the fathead minnow (Pimephales promelas) were investigated by Alexander et al. (1981), who report a 96-h LC50 value of approximately 16,000 ppm, suggesting that at least this inorganic bromide has a relatively low acute toxicity. In addition, background concentrations of bromide in sea water are also relatively high. Consequently, any residual bromide present in produced water flows containing completion fluids would rapidly reach background levels within a few metres of discharge sites.

2.4 Blowout Preventer (B.O.P.) Control Fluid

The primary constituent of B.O.P. hydraulic control fluids used in Canadian drilling operations is ethylene glycol, which has been shown to be "moderately toxic" to aquatic fauna but also rapidly degraded by numerous bacteria found in sea water. For example, Price et al. (1974) found that the 24-h median tolerance limit of brine shrimp (Artemia salina) to ethylene glycol exceeded 20,000 ppm. On the other hand, B.O.P. control fluid may be relatively toxic to some species of crustaceans, for Portman and Wilson (1971) reported that the 48-h and 96-h LC50 values of ethylene glycol with the brown shrimp (Crangon crangon) were only 100 ppm. The microbial breakdown of glycols, and the ability of certain strains of bacteria (primarily those of the genus Pseudomonas) to use ethylene glycol as their sole carbon source, were reviewed by Miller (1979). The widespread occurrence of bacteria capable of degrading ethylene glycol likely relates to the simple nature of the molecule and its relationship to components of various metabolic pathways. The biological effects of routine B.O.P. control fluid release at offshore hydrocarbon exploration and production sites have not been directly investigated, although the rapid dilution of this waste with increasing distance from B.O.P. stacks would limit the biological effects and environmental concern associated with hydraulic control fluid discharge, particularly in offshore waters where accumulation or persistence in receiving waters would be extremely unlikely.

2.5 Cement Slurry

Cement is used during drilling operations to grout the upper casings to the riser at floating and platform drill rigs. The impacts of grouting operations on marine flora and fauna do not appear to have been examined in offshore hydrocarbon exploration and production areas, but adverse effects would be extremely local due to the small quantities of waste involved, the limited zone of influence of cement slurry before it hardens, and the infrequent nature of this discharge (usually once in the life of a well). Physical and chemical effects of cement slurry discharge that may have subsequent local impact on marine flora and fauna include: (1) increases in water and sediment pH caused by dissolution of alkaline compounds in cement; (2) local and temporary increases in water turbidity; and, (3) loss of benthic habitat in areas where cement slurry hardens.

Discharge of excess cement slurry during grouting operations at offshore wells would have its most significant impacts on sessile epifauna (e.g., hydroids, anemones) and relatively immobile infaunal invertebrates (e.g., bivalve molluscs, polychaetes). The magnitude and duration of the physical and chemical effects of cement discharge on benthic organisms have not been examined directly in areas of offshore hydrocarbon exploration or production, but mortality and substrate loss by smothering and alteration of the physical characteristics of the substrate would only be expected over relatively small areas.

3.0 Ballast and Storage Displacement Water

Ballast water is pumped aboard tankers bound for oil loading facilities to maintain stability when not carrying cargo, and depending on tanker design, is either transported within the oil compartments or in segregated ballast tanks. Ballast water transported in oil compartments is treated to reduce content of petroleum hydrocarbons prior to discharge. Ballast transported in segregated tanks, however, is not contaminated with oil under normal circumstances and is directly discharged.

The annual world-wide input of petroleum hydrocarbons to the marine environment is estimated at 6 million tonnes (National Academy of Sciences 1975), with approximately 35 percent of this volume resulting from marine transportation activities. Of the overall input of oil to the world's oceans from marine transportation, ballast water and tank washings are the largest single sources of contamination (Birchard 1980). The amount of petroleum hydrocarbons entering the marine environment from ballast discharge will gradually be reduced as segregated ballast vessels become more common.

Facilities for storage of crude oil are required at some offshore loading terminals to provide sufficient volume of cargo to minimize loading time and accommodate tanker delays. The chronic release of oil into the environment through discharge of storage displacement water is an area of continuing environmental concern (Read and Blackman 1980), although this waste is only slightly contaminated with hydrocarbons because oil and water only contact each other at an interface.

The production of H_2S and its oxidation to sulphuric acid, resulting from growth of sulphur-reducing bacteria in stagnant water, has been an unexpected side effect of displacement water storage in North Sea offshore facilities. Such activity occurs only after oxygen in the stored water has been depleted. The production of H_2S poses a safety hazard to personnel and formation of sulphuric acid accelerates structural corrosion. However, deleterious effects from discharges to the marine environment have not been studied (Wilkinson 1982).

Ballast effluent characteristics and the capacity of the receiving waters for dilution and dispersion of effluents influence the potential biological effects of oily discharges (Johnston and Halliwell 1976). In areas characterized by relatively high suspended sediment levels, adsorption of oil to particulate matter could cause rapid sinking of a proportion of the oil near discharge sites. The potential effects of this fraction would depend on the rates of sedimentation and subsequent biodegradation of oil.

In most instances, wastewater treatment technologies are relatively successful in removing suspended oil from ballast and storage displacement water. Water soluble fractions of oily waste waters are less effectively removed during the oil/water separation processes than dispersed oil. Soluble aromatic hydrocarbons represent a major fraction of the oil content of ballast water after treatment. The concentrations of dissolved aromatic hydrocarbons and resultant toxicity of storage displacement water effluent would typically be lower than ballast water because of the more limited opportunity for mixing and dissolution of the soluble components.

Rice et al. (1981) examined ballast water treatment effluent from the Port of Valdez (Alaska) and reported that the treated effluent contained light aromatic hydrocarbons in the range from 1-16 ppm. The toxicity of petroleum hydrocarbons is primarily related to the availability and concentration of soluble aromatics, with acute lethal concentrations ranging from 0.1 ppm to 100 ppm for various classes of marine biota. Larvae are usually 10-100 times more sensitive to petroleum hydrocarbons than adults (Kuhnhold 1970), while sublethal effects have been demonstrated at aromatic hydrocarbon concentrations as low as 10-100 µg/L (Anon 1974).

Studies of the effects of treated ballast effluent from Port Valdez on marine invertebrates and fish were conducted by Rice et al. (1981). For the larvae of crustaceans and fish, the static bioassay 96-h LC50 values ranged from 10 to 20 percent treated effluent, while the concentrations of total aromatic hydrocarbons in these tests were generally within the range of 0.5 to 3 ppm. In flow-through bioassays, the 48-h LC50 values for salmon fry and shrimp ranged from 20 to 40 percent treated effluent (0.8-2.8 ppm total aromatic hydrocarbons). Rice et al. (1981) reported that the aromatic hydrocarbons were not the sole cause of the effluent toxicity, but that it was difficult to define the contributions of other constituents to the toxicity of treated Port Valdez ballast water.

These data suggest that at the point of discharge levels of soluble aromatics in treated ballast and possibly storage displacement water could be within the range which has been shown to be acutely toxic or capable of producing sublethal stress on some marine biota. The extent of mortality or sublethal effects on pelagic and benthic organisms would depend on the volume and rate of ballast water discharge, and on the subsequent dispersion of effluents in the receiving environment. In most instances, aromatics would be rapidly diluted to levels below toxic and sublethal thresholds within a short distance of the outfall.

There is field evidence which shows the accumulation of petroleum hydrocarbons in the sediments in the immediate vicinity of some North Sea oil and gas platforms (Oppenheimer et al. 1977). Concentrations of hydrocarbons in water were estimated, by calculation, to meet water quality objectives in bottom waters within 1000 m of the discharge point (Read and Blackman 1980). These authors emphasized that more than 95 percent of the oily wastes discharged to this near shore area originate from produced waters, with the remainder resulting from storage displacement water and other sources. More recent estimates of oily waste discharges from North Sea operations indicate that oil on cuttings is the largest source.

4.0 Produced Sand

Produced sand is the solid material that comes to the surface with reservoir fluids. The effects of produced sand have apparently not been directly examined in offshore production areas.

The main biological concerns related to the discharge of produced sand are: (1) the potential for chronic introduction of petroleum hydrocarbons to the marine environment; (2) local increases in water turbidity; and , (3) sand deposition in benthic habitats. The biological significance of these effects would vary with the amount of sand discharged, the method and location of discharge, degree of contamination of the sand by oil, and finally, the prevailing oceanographic conditions which affect rate of settling and dispersion. The total amount and rate of produced sand discharge vary within and among production fields, with the greatest amounts of sand generally being produced late in the life of a production field.

The volumes of produced sand that are discharged and the oil content of cleaned sand are generally low. Potential effects on infauna would be local and indistinguishable from effects of the cumulative oil discharge at production platforms.

5.0 Sanitary and Domestic Wastes

Biological concerns associated with the discharge of sanitary waste (sewage) relate to the potential for nutrient enrichment, oxygen depletion of receiving waters, smothering of benthic organisms, transmission of disease, and toxicity of residual chlorine. The extent of these effects is dependent on the ability of receiving waters to accept, dilute and disperse the sewage effluent. Potential concerns regarding discharge of domestic waste (grey water) include foaming of receiving waters when non-biodegradable detergents are used, and localized enrichment of receiving waters due to the phosphate content of detergents (IMCO et al. 1977). Globally, the open ocean and most small seas have not been seriously affected by sewage discharges (Topping 1976). Sewage has only resulted in documented effects on marine communities in nearshore areas with poor circulation, bays, fjords and estuaries near major centers of human population (Ryther and Dunstan 1971; Berg 1975).

The volume and concentration of sewage and gray water produced at offshore facilities varies widely with occupancy, platform characteristics, and operational situations (Chapter 2). Nevertheless, the overall volume of sanitary and domestic wastes discharged from production platforms is relatively small, with a typical average of 20 m^3 of sewage and 30-40 m^3 of domestic waste per day. Consequently, any effects of these wastes on marine biota and water quality would be local, and in most instances restricted to the vicinity of the outfall, except in shallow, nearshore areas.

6.0 Oil and Gas Processing Wastes

Liquid wastes produced during the processing of oil are derived primarily during the separation of produced brine from crude oil. Discharged oily wastes contain residual crude oil and small amounts of various organic additives other than hydrocarbon compounds. Liquid processing wastes are usually collected in sumps and the oily water is treated in the produced water treatment system. Chemical additives used for corrosion inhibition include chromates and zinc salts. Chemicals which may be used to aid in the breakdown of emulsions during the oil-water separation process include phosphate esters, quaternary amines, and aromatic and alcohol solvents. Biocides added downhole and to processing units include aldehydes, quaternary amines and pentachlorophenol, although the latter is now largely prohibited. Dosages up to 100 mg/L are used. A number of chemicals used are environmentally persistent or are toxic to marine organisms. The chemicals are used in small quantities and are generally soluble in oil, but unknown amounts do dissolve in produced water and subsequently enter the marine environment.

The effects of the chronic low-level release of chemicals at offshore platforms have not been documented per se but are not expected to be regionally significant because:

(1) the amounts discharged are thought to be small; little documentation has been made confirming this conclusion;

(2) the capacity of the open ocean for dispersion and dilution is high; and

(3) in general, most of the chemicals (although not all) are not highly toxic to marine organisms.

For example, alcohol solvents are miscible with sea water, not accumulated by marine organisms, and are rapidly biodegradable to harmless substances (IMCO et al. 1977). The addition of phosphate esters could lead to local enhancement of primary production under certain conditions, although there is no evidence to suggest that the low concentrations associated with oil processing wastes would have significant effects. With the exception of ammonia, most forms of nitrogen are not considered directly harmful in receiving waters. In some conditions, amines may be reduced to ammonia which is toxic to marine biota in its non-ionized (NH_3) form

(Hrudey 1979). However, the potential effects of this discharge are still expected to be small because of the small quantities of ammonia that could reach the marine environment and the dilution capacity of the open ocean.

Wastes produced with the processing of gas are derived mainly from chemicals used in the dehydration process, including glycol and ethanolamine. The quantity of chemicals used varies with the size of the gas processing facilities. Minor losses of these chemicals to the marine environment may occur at offshore processing facilities, largely through the deck drainage system. The potential effects of most sweet gas processing wastes on marine biota, however, would be insignificant due to the small amounts discharged in relation to the diluting capacity of the open ocean. Offshore facilities processing sour gas, which contains acidic constituents such as hydrogen sulphide, have not been studied. Therefore, no conclusion can be drawn regarding the effect of waste discharges from offshore sour gas processing facilities. Few offshore facilities produce sour gas.

CHAPTER 5

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CHAPTER 6

MARINE DISCHARGE REGULATIONS

1.0 Current Canadian Regulations

The Canada Oil and Gas Lands Administration (COGLA) has prepared draft regulations for offshore Canadian oil and gas production. Existing legislation includes offshore oil and gas exploration and general guidelines for handling and storage of fuel, drilling fluids, solid wastes and oil and gas produced during formation flow tests (Tables 6-1 and 6-2). The draft production regulations include a limit for oil concentration in produced water discharges; however, the only regulations for discharge of drilling muds and cuttings are that general waste disposal requirements must provide adequate levels of environmental protection acceptable to the Chief. An oil content in produced water discharges of 35 mg/L "or a maximum daily carry over volume as may be specified by the Chief" are specified in the draft COGLA regulations, but the draft does not indicate whether the 35 mg/L is a maximum, average, daily or monthly concentration, or which carry over volumes may be specified. The basis for the 35 mg/L oil requirement has not been clearly stated by COGLA; that is, whether the level is based on implementation of Best Practical Technology, Best Available Technology, or known or potential environmental effects. There is also no indication of the analytical method to be used to determine compliance with the 35 mg/L limit on oil in produced water.

The Canada Ocean Dumping Control Act based on the London Dumping Convention, also includes regulations for waste discharges; however, it excludes discharges from oil and gas operations. The Act stipulates a limit of less than 10 mg/L for oil and petroleum hydrocarbons in wastes; concentrations of organohalogens, mercury, cadmium and persistent synthetics or plastics in wastes are also limited by the Act.

TABLE 6-1

REGULATIONS FOR OIL AND GAS PRODUCTION WASTES: DRILLING MUDS AND CUTTINGS AND PRODUCED WATER

	DRILLING MUDS AND CUTTINGS		PRODUCED WATER			
	Water-Base	Oil-Base	Mean Oil Content Monthly Average mg/L	Mean Oil Content Daily Average mg/L	Trace Metals mg/L	Additives and Other Chemicals
Canada	Approved disposal that does not create hazard to health, safety or environment[7]	Oily materials not to be burned at drillsite; proper shore disposal oil or oily material not disposed into surface waters[7]		35[1]		
USA	No discharge of wastes into navigable waters. Exceptions by permit[3]	No discharge of wastes into navigable waters. Exceptions by permit. No discharge of free oils[3]	48[3] (GR)	72[3] (GR)		
Region IX California	No visible floating solids. No discharge of toxic materials which after allowance for initial mixing exceeds limiting permissible conc.[5]	Discharge of oil-base muds prohibited. Oily cuttings shall produce no free oil on surface.		72[5] (GR)	• As 0.032; Cd 0.012; Cr 0.008; Cu 0.02; Pb 0.032; Hg 0.00056; Ni 0.08; Ag 0.0018; Zn 0.08; Phenols 0.120; Cyanide 0.02[5,6]	Halogenated phenols prohibited. Surfactants, dispersants and detergents-discharge minimized except to comply with health and safety requirements[5]
Region VI Gulf of Mexico	No discharge of floating solids or visible foam[14]	same as Region IX[14]		72[14] (GR)		Same as Region IX[14]
Region X Cook Inlet			48[6] (GR)	72[6] (GR)		Produced water pH-min. 6.0; max. 9.0 Deck drainage oil and grease average 65 mg/L, max. 90 mg/L[6]
Norway	Drilling mud of approved composition and cuttings may be discharged into the sea in such as manner as to ensure rapid dilution[2]	Approved treatment method and holding facility for spent mud, and cuttings required.[2] Allowable oil in cuttings 50 to 150 L/m^3 [13,17]		25 large facility 30 small facility[15,17] (IR)		
Great Britain	Offence to dump substances in territorial waters. Permits may be issued in exception[8]	Discharge of drilling mud prohibited - exceptions may be granted. Cleaned cuttings may be discharged with no restriction on oil content. New standards are proposed to limit oil in cuttings to 5% of dry wt. for diesel-base systems. No limit or 15% oil on cuttings are being considered for paraffin-base systems[11,8]	40 (IR) large facility 30 (IR) small facility[11]		Prohibited to discharge organohalogens; mercury and cadmium and their compounds; persistent plastics and persistent oil and grease[11]	Voluntary notification scheme which classifies products based on toxicity[18].
Denmark			40[15]			
France			20[15]			
Australia (State of Victoria)				30 (max 50)[15]		

TABLE 6-2

REGULATIONS REGARDING OIL AND GAS PRODUCTION WASTES OTHER THAN DRILLING WASTES AND PRODUCED WATER

	SANITARY AND DOMESTIC WASTES	NON-COMBUSTIBLE SOLID WASTES	BALLAST WATER	OTHERS
Canada	Suspended solids - the lesser of 10 percent effluent conc. or 75 mg/L; fecal coliform <400/100 mL BOD <50 mg/L[1]	Approved land disposal[1]		Spent acid approved disposal method[1]
USA-EPA	No floating solids <1 mg/L residual chlorine[3]			Deck drainage and well treatment fluids no discharge of free oil[3]
Region X Gulf of Alaska	pH; Min. 6.0, Max. 9.0[4]		pH; Min. 6.0, Max. 9.0, Oil and grease mean 8 mg/L; max. 10 mg/L[4] Aromatic hydrocarbons mean 6 mg/L, max. 9 mg/L[4]	Deck drainage oil and grease, max. 90 mg/L[4]
Region IX California	No floating solids. Approval for discharge with use of any marine sanitation device that complies with pollution control standards. <1.0 mg/L residual chlorine[5]			No discharge of free oil due to discharges of deck drainage, produced sand, well completion or treatment fluids[5]
Region VI Gulf of Mexico	Same as Region IX[14]			No discharge of free oil from deck drainage, or well treatment fluids[14]
Norway	Pollution authority may specify treatment methods and discharge levels. Clean food wastes may be dumped overboard[2]	Waste including harmful or poisonous chemicals- and substances, objects iron, steel or concrete etc. shall be transported to approved shore disposal[2]	Treated (best available technology) ballast water may be discharged[2]	Discharge water containing substances harmful to marine environment must be purified in accordance with State Pollution Control Authority[2]
Great Britain	No restrictions on offshore discharge[12]	Dumping of any substances or articles an offence without licence. All waste materials should be disposed of ashore. Exceptions may be granted by permit.[8]	Prohibited to discharge oily wastes, exceptions granted by permit. Conc. limit based on best available technology[9] (generally permits for onshore terminals require 5-25 mg/L IR-oil limit[16,18]) Offshore limit is 40 mg/L IR-oil	

REFERENCES AND NOTES FOR TABLES 6-1 and 6-2

1. COGLA 1982 Draft Regulations for Oil and Gas Production

2. Provisional regulations concerning littering and pollution caused by petroleum activities. Norwegian Petroleum Directorate 1979

3. U.S.A. Federal Register 44 (73) Apr. 13/79, Part 435.12 EPA NSPS

4. pers. comm. Sikorski. U.S.A. EPA Point Source Permits for individual operators.

5. U.S.A. Federal Register 47 (33) Feb. 18/82, California NPDES Permit

6. These limits apply after initial dilution within a defined mixing zone. Compliance with these limits shall be determined through the use of the following equation: $C_e = C_o + D_m (C_o - C_s)$ where:

   C_e = the maximum allowable concentration
   C_o = the concentration which is to be met at the completion of initial detection
   D_m = minimum probable initial dilution expressed as parts sea water per part wastewater
   C_s = background seawater concentration.

7. Canada Oil and Gas Exploration Drilling Regulations P.C. 1979-25 amended by P.C. 1980-2111 Nov. 1980.

8. George and Read 1979

9. U.K. Prevention of Oil Pollution Act 1971

10. U.K. Dumping at Sea Act 1974

11. pers. comm. Davies.

12. pers. comm. Read.

13. Schreiner 1980

14. U.S.A. Federal Register 46 (64) Apr. 3/81 - Gulf of Mexico NPDES Permit

15. Read 1980

16. Moore 1980

17. Norway State Pollution Control Authority. Guidelines for operators concerning application for continuous effluents discharge from the petroleum operations on the Norwegian Continental Shelf. January 17, 1982

18. pers. comm. Johnston

GR Gravimetric analysis for oil
IR Infrared analysis for oil
UV Ultraviolet analysis for oil

2.0 United States

The United States Environmental Protection Agency (EPA) regulations for the oil and gas extraction industry limit oil and grease content in discharges of produced water, deck drainage, drilling muds, drill cuttings, and well treatment fluids (Tables 6-1 and 6-2). Regulations for domestic waste discharges are also included. A 48 mg/L maximum monthly average and 72 mg/L daily maximum oil content for produced water discharges are stipulated in the New Source Performance Standards (NSPS) which were developed by statistical analysis of data for gas flotation unit effluents from existing produced water discharges into coastal and offshore waters of the U.S. Gravimetric analysis is the method stipulated for determination of oil concentrations. A "no free oil" discharge limitation applies to all other effluents (deck drainage, drilling muds, drill cuttings and well treatment fluids). This requirement is commonly known as the "no surface sheen and no bottom emulsion" restriction, which allows ready detection of violations by the enforcement agency (U.S. Coast Guard), but is difficult for the industry to meet consistently.

The Clean Water Act is the legislation from which the NSPS derives its regulations. Authority is provided in the Act for Regional EPA offices to issue regional (general) or individual permits that are more or less stringent than specified by the NSPS. Two EPA Regions (California and Gulf of Mexico) have issued general permits, which cover all offshore oil and gas production discharges in federal waters (beyond 5 km for most areas, 16 km for the Texas and West Florida coast) (Tables 6-1 and 6-2). Once issued, these permits (National Pollution Discharge Elimination System (NPDES) General Permits) allow all conforming offshore platforms to discharge those wastes specified in the permit, without additional licensing. NPDES Permits are technology based. Depending on the pollutant and the available technology, discharge limits are specified, but control technologies for each waste are not specified. The California NPDES permit includes restrictions on trace metal concentrations in produced water effluents. The California and Gulf of Mexico regions each limit oil in produced water effluents and each region prohibits discharges of halogenated phenols, and controls surfactants, dispersant and detergent discharges, although no numerical limitations have been specified. Both regions have instituted only a maximum daily limit of 72 mg/L of oil in water discharges, and prohibit the marine discharge of oil-base drilling muds. The U.S. EPA has not yet adopted a general permit for Alaskan waters and uses individual permits for each platform and discharge source. Permits reviewed for this report (pers. comm. Sikorski) included the NSPS for oil content in produced water, (42 and 72 mg/L), and less stringent conditions for deck drainage (average 65 mg/L and maximum 90 mg/L).

3.0 Great Britain

The legal basis for British continental shelf law is the Petroleum (Production) Act 1934 which provides that petroleum resources in British lands are vested in the crown, and the more recent Continental Shelf Act 1964 which controls the "shelf adjacent to the United Kingdom". The Department of Energy issues Exploration and Production Permits through these Acts, which contain the condition that operations be carried out in such a manner as not to interfere with fishing and conservation of living resources. Permits are awarded on a discretionary basis and a satisfactory work program must be included. Onshore terminals handling crude oil from offshore platforms are subject to local approvals procedures, which include limits on oily waste discharges. The Dumping at Sea Act (1974) states that it is an offence for substances to be dumped in U.K. territorial waters, and a notice for Continental Shelf Operation recommends that all waste materials be disposed of ashore (George and Read 1979). The discharge of oily water and oily wastes (except light oils such as diesel) is prohibited by the Prevention of Oil Pollution Act (1971). U.K. ratification of the MARPOL Convention has resulted in diesel and other light oils being included in the definition of oil; as of October 1983, oily cuttings are covered by the Act. Exemption from the provisions of the Act has been granted by the Secretary of State for Energy to offshore installations using the best practical means available to reduce oil content in discharges. An oil content limit is based on equipment performance standards and the accepted provisional target is 40 mg/L monthly average for large installations or 50 mg/L for small installations (determined by infrared analysis). There is presently no restriction on the amount of oil in cleaned cuttings discharges, however, some regulations are under consideration (pers. comm. Davies; see Table 6-1). Sewage and domestic wastes disposal are not regulated at offshore facilities; however, discharge of mercury, cadmium, plastics and organohalogens, are prohibited (as per the Paris Convention and the London Convention on Dumping), (pers. comm. Davies) (see Table 6-3).

The U.K. uses a "Notification Scheme for the Selection of Chemicals for Use Offshore" which classifies chemicals according to a scale of toxicity andbiodegradability (Read and Whitehead, 1981). For example, materials which are highly toxic to marine organisms or are persistent in the marine environment, such as mercury, cadmium, cyanide, organotins, organophosphorus compounds, polychlorinated biphenyls and chlorophenols, are to be avoided. The next level on the scale includes arsenic, copper, lead, zinc and other metals which should not be used if discharge concentrations are likely to exceed 100 mg/L. Notification of the intent to use chemicals in the offshore and the amount to be used allows the producing industry and government flexibility in making case-specific decisions on chemical use.

4.0 Norway

Norwegian offshore oil and gas production discharges are controlled by the Provisional Regulations Concerning Littering and Pollution Caused by Petroleum Activities (1979) and Regulations for Production Etc. of Submarine Petroleum Resources (1979). Guidelines have been prepared for continuous effluent discharges. These regulations and guidelines include general restrictions on the dumping of poisonous chemicals and substances, objects of iron, steel or concrete and state that these wastes must be transported to shore for disposal. Requirements for seabed monitoring before and after production are used to enforce the proper disposal of wastes. While clean food waste may be dumped overboard, sewage treatment and disposal limits may be set by the Pollution Authority for specific installations. The discharge of oily wastes such as produced water, oil-base drilling muds and cuttings is strictly controlled by permits to individual operations. Strict monitoring requirements are also imposed. The permitted oil concentration is based on the best available technology which allows for a reasonable relationship between expenses incurred and environmental benefits (Fretheim 1980). Total loading of oil discharged to the sea from each platform is controlled by limits on oil concentrations and effluent volumes in produced water, deck drainage and other oily wastes. The oil content of the discharge from large facilities is limited to an average of 25 mg/L and that from small facilities to 30 mg/L based on random sampling. The use of oil-base drilling muds is also subject to permit and the pre-treatment method and holding facilities for oiled cuttings must receive prior approval. The discharge of cleaned cuttings is controlled by permit; the maximum allowable oil content varies from 50 to 150 L/m^3. The discharge of water-base drilling muds (of approved composition) and cuttings is also controlled by permit. (See Table 6-1 for these regulations and oil discharge limits for produced water for Denmark, France and Australia).

5.0 Comparison of International Conventions and Oil and Gas Production Legislation

Several international conventions include discharge limits for oil, solid wastes, trace metals and other chemical substances that may be associated with offshore oil and gas production activities. The three most relevant conventions are the London Convention on Dumping, the International Convention for the Prevention of Pollution by Ships, and the Paris Convention. These conventions as well as relevant Canadian legislation (Shipping Act and Ocean Dumping Control Regulations) are summarized in Tables 6-3 and 6-4.

The most stringent requirements regarding oil discharge appear to be in the Canada Shipping Act and MARPOL conventions for internal waters (Table 6-4). The Canada Shipping Act prohibits discharge of oil in territorial seas and national waters to the 320-km (200-mile) limit, because Canada has not ratified MARPOL; this is presently under review (pers. comm. Schormann). The ratification of MARPOL would result in allowable oil discharge of 15 mg/L in ballast waters and less than 100 mg/L in tanker bilge when ships are enroute and greater than 19 km (12 mi) from shore. Current world regulations for oil discharges from offshore oil and gas production facilities fall between these two extremes. Norway and France have the most stringent restrictions, allowing 25 and 20 mg/L, oil discharge respectively and the U.S. has the highest allowable discharge of 72 mg/L maximum mean daily oil content (Table 6-1). Norway and the U.S. each base the allowable oil discharge on best available technology which is economically achievable.

The Paris Convention and the London Convention on Dumping recommend that discharge of organohalogens, mercury and cadmium and their compounds, persistent plastics and synthetics and persistent oil and hydrocarbons be eliminated (Table 6-3). Canada (Ocean Dumping Control Regulations) allows these substances to be discharged at prescribed, low levels with a permit. The U.S. NPDES permit for offshore California oil and gas production also allows discharge of mercury and cadmium at low concentrations, in produced water, but prohibits the discharge of halogenated phenols. California and Gulf of Mexico NPDES permits include discharge limits for additives and other chemicals. These permits each place qualitative restrictions on discharge of surfactants, dispersants and detergents (Table 6-1). Draft Canada Oil and Gas Production Regulations do not include discharge limitations for trace metals, additives or other chemicals.

TABLE 6-3

INTERNATIONAL CONVENTIONS AND CANADIAN LEGISLATION (OTHER THAN OIL AND GAS PRODUCTION) CONCERNING SELECTED WASTE DISCHARGES

	PARIS CONVENTION	LONDON CONVENTION ON DUMPING	CANADA OCEAN DUMPING CONTROL REGULATIONS
Organohalogens	1	3	5 - <0.01 parts of a conc. shown to be toxic to sensitive organisms in an approved bioassay
Mercury and Hg compounds	1	3	5 - 0.75 mg/kg solids 1.5 mg/kg liquid
Cadmium and Cd compounds	1	3	5 - 0.6 mg/kg solid 3.0 mg/kg liquid
Persistent synthetics or plastics	1	3	5 - 4 percent by vol. in a suitably comminuted form
Persistent oils and hydrocarbons	1	3	5 - <10 mg/kg
Organic compounds of phosphorous, silicon or tin	2	4	6
Arsenic and compounds	2	4	6
Chromium and compounds	2	4	6
Copper and compounds	2	4	6
Lead and compounds	2	4	6
Nickel and compounds	2	4	6
Zinc and compounds	2	4	6
Vanadium and compounds		4	6
Cyanides and compounds		4	6
Containers, scrap metal other wastes liable to sink and present an obstacle to fishing or navigation		4	6

1 Discharge should be eliminated
2 Discharge should be strictly limited
3 Dumping is strictly prohibited
4 Special permit for discharge required in advance
5 Prohibited substances whose discharge concentrations is limited and for which a special discharge permit is required.
6 Restricted substances for which a special permit for discharge is required in advance.

TABLE 6-4

INTERNATIONAL CONVENTIONS AND CANADIAN LEGISLATION (OTHER THAN OIL AND GAS PRODUCTION) CONCERNING OILY WASTE DISCHARGES

DISCHARGE STANDARDS	SHIP BILGES			CLEAN BALLAST	OTHER SOURCES
	>150 tons	<400 tons	>400 tons		
MARPOL* and Protocols Internal Waters	**	Extent Practical	$\leq$ 15 ppm	$\leq$ 15 ppm***	
Exclusive Economic Zone	**	Extent Practical	En route >12 mi from land <100 ppm	$\leq$ 15 ppm***	
Arctic Shipping Safety Control Zone	**	Extent Practical	$\leq$ 15 ppm or en route >12 mi from land <100 ppm	$\leq$ 15 ppm***	Oil tanker tank washings < 60L/ nautical mi; provide slop tanks and monitoring equipment
Paris Convention Provisional target for all discharges					40 ppm
London Convention on Dumping			Oily mixtures are not covered by this convention		
Canada Ocean Dumping Reg.					<10 mg/kg of n-hexane soluble substances
Canada Shipping Act			No oil discharge		

* International Convention for the Prevention of Pollution from Ships, 1973; 1978 Protocol to the International Convention for the Safety of Sea, 1974

** Pollution control equipment, oil filtering devices, pollution monitoring equipment, oily water separators and oil record book

*** New crude oil tankers of $\geq$ 20,000 tons deadweight and every new product carrier of $\geq$ 30,000 tons deadweight shall be provided with segregated ballast tanks, and existing crude oil tanks of $\geq$ 40,000 tons deadweight shall be provided with segregated ballast tanks. In no case shall ballast water be carried in cargo tanks except in weather conditions that threaten the safety of the ship.

The Canada Ocean Dumping Control Regulations are based upon the London Convention on Dumping and both these documents require that permits be issued for any discharge of solid wastes into the ocean (Table 6-3). Draft COGLA regulations include a recommendation for land disposal of non-combustible solid wastes. In the North Sea, Britain allows ocean dumping with a permit and Norway requires land disposal of solid wastes. The U.S. does not include solid waste disposal regulations in NPDES permits (Table 6-2). Domestic waste disposal requirements in the draft COGLA regulations are more stringent than the Ocean Dumping Regulations in that they indicate maximum levels of suspended solids, fecal coliforms and BOD, whereas there is no restriction on sewage discharge in the Ocean Dumping Regulations (presently under review; pers. comm. Schormann). In this area Canada's proposed oil and gas regulations are more specific than those of the U.S., Great Britain or Norway. While Great Britain and Norway have no regulations for domestic waste discharges from offshore production facilities, the U.S. EPA restricts floating solids and requires a minimum chlorine concentration (Table 6-2). NPDES permits for California and Gulf of Mexico include requirements for use of an approved sanitation device.

CHAPTER 6

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3. J. Sikorski. U.S.A. Nov. 1, 1982. EPA Region X. Seattle.
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CHAPTER 7

CANADIAN OFFSHORE PRODUCTION SCENARIOS

1.0 Production Scenarios

1.1 Introduction

Three offshore regions in Canada have had sufficient hydrocarbon potential identified through exploratory drilling to warrant the introduction of development plans and preliminary design work. Figures 7-1 and 7-2 show the location of these regions and identify the major hydrocarbon discoveries to date. A number of gas fields have been identified within a few kilometres of each other on the Scotian Shelf, in the Atlantic Ocean off Nova Scotia. Three overlying and adjacent oil fields have been discovered on the Grand Banks in the Atlantic Ocean off Newfoundland. A number of oil and gas fields have been discovered in the Mackenzie Delta and southern Beaufort Sea areas of the western Canadian Arctic. While exploration activities are taking place or are planned in a number of other offshore regions of Canada (the west coast of British Columbia, the Arctic Islands, off the north and east coasts of Baffin Island, and coastal Labrador), no important hydrocarbon discoveries have been made and no offshore development proposals have been brought forward.

Offshore production scenarios for the three promising regions of Canada have been developed in this report for the following reasons:

(1) to provide a general description of offshore development activities planned for these waters;

(2) to allow information gathered on industry and government practice in existing offshore producing areas of the world to be applied to Canadian areas,

(3) to allow generation of typical offshore production waste estimates for use in a plume dispersion model depicting 'zones of influence' around each development;

(4) to provide the basis for identifying potential environmental concerns related to production waste discharges in each of these three Canadian offshore regions.

Major sources of information for these scenarios are meetings with officials of companies preparing development plans for each region, company documents and

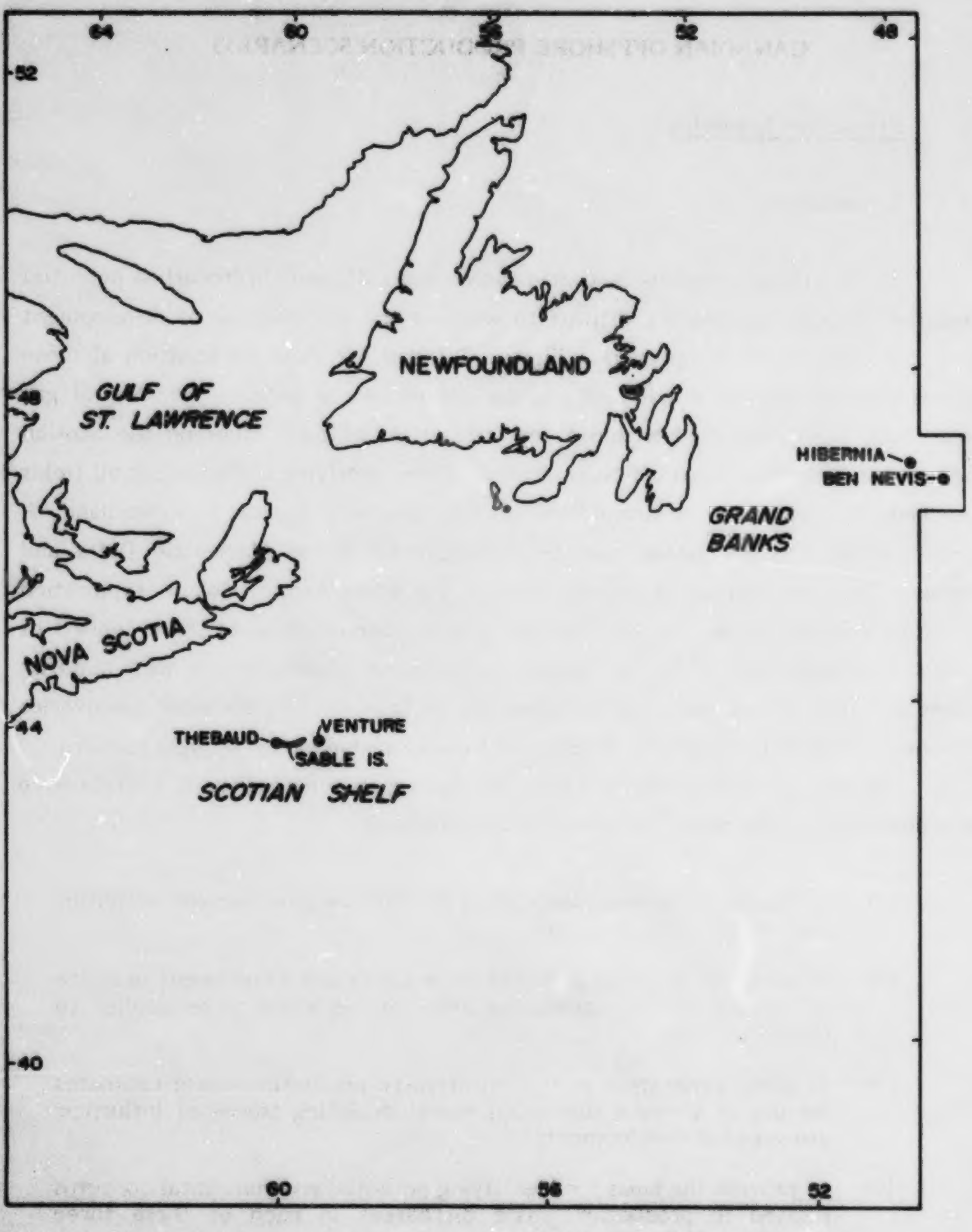
64
60
56
52
48
52
48
44
40
NEWFOUNDLAND
GULF OF
ST. LAWRENCE
HIBERNIA
BEN NEVIS
GRAND
BANKS
NOVA SCOTIA
THEBAUD
VENTURE
SABLE IS.
SCOTIAN SHELF
60
56
52

FIGURE 7-1. Approximate locations of anticipated hydrocarbon development on the Scotian Shelf and Grand Banks off the coast of Eastern Canada.

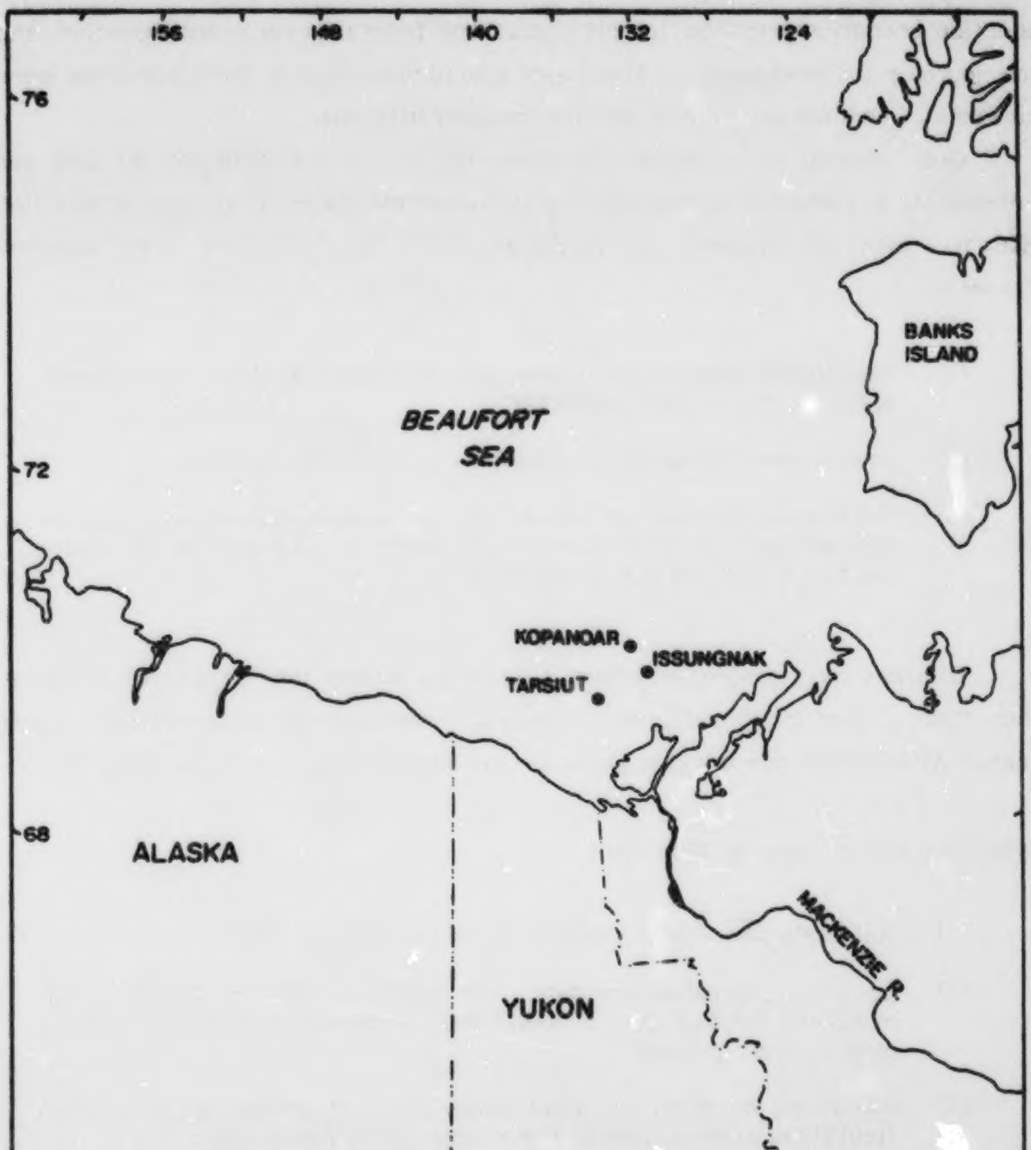
156
148
140
132
124
76
72
68
64
148
140
132
BANKS ISLAND
BEAUFORT SEA
KOPANOAR
ISSUNGNAK
TARSIUT
ALASKA
YUKON
MACKENZIE R.

FIGURE 7-2. Approximate location of anticipated hydrocarbon development in the Canadian Beaufort Sea.

submissions to government agencies, economic and technical evaluations of offshore production scenarios prepared for provincial and federal government agencies, and trade journals and newspapers. The major assumptions used in these scenarios were reviewed by Canadian government and oil company officials.

Only general non-site-specific scenarios for future offshore oil and gas developments in Canadian waters and the attendant estimates of offshore production waste treatment technology and discharge characteristics have been assessed because:

(1) insufficient information is available to develop specific development plans for the regions and fields,

(2) development scenarios are changing for all three regions,

(3) the world literature and experience provides better information for the purposes of this study, particularly for estimation of waste discharge volumes and characteristics.

Offshore development has been considered within the context of a typical rather than a specific development scenario developed for each region. These scenarios assume that one world-scale oil or gas field is developed in each region.

Assumptions for the general scenarios:

(1) full-scale development of one oil or gas field for each region;

(2) no specific development dates; the scenarios focus on concentration of effort; for example, 20 wells drilled from each of two platforms over a 2-year period;

(3) conditions of operation after 10-20 years of production from each field (typical conditions at the middle of the field's life);

(4) Some parameter values have been taken from information for a specific field in each region (such as well depth). Other information is based on regional (Canadian) and world information, while remaining typical of the region under consideration.

1.2 Scotian Shelf

A gas field is located about 15 km east of Sable Island on the Sable Island Bank of the Scotian Shelf and 180 km from the Nova Scotia coast. Water depth is approximately 20 m. The field has an estimated recoverable reserve of 85 billion m^3 (3.0 tcf).

The design gas production rate of the field is assumed to be approximately 11 million m^3/d (400 MMSCFD) for about the first 15 years, decreasing with decreasing reservoir pressure. Gas condensate production is assumed to be approximately 1000 m^3/d, (6000 bbl/d). Accurate estimates of produced water volumes are unavailable. Estimates presented in Section 3 of this chapter are based on world experience with offshore gas production.

The shallow water and ice-free conditions at the proposed production site permit the use of offshore gas production platform technology as used in other parts of the world. Different activities are physically separated on separate fixed platforms. A well-head platform for operating and maintaining the wells, a platform for processing the reservoir fluids before transmission to shore with a dense-phase pipeline, an accommodation platform and a gas flaring structure for safe disposal during upset conditions, comprise the production unit. All platforms are connected by walkways.

The single well-head platform services 40 wells, although not all wells feed gas to the platform at the same time. The wells are drilled over a period of 3 years. All drilling wastes are discharged from this single platform. For the purpose of evaluating the overlap of waste discharge zones of influence (Chapter 8), a set of three platform clusters between 8 and 16 km apart has been assumed.

The processing platform cools and separates gas, condensate, and free water from the reservoir fluids. All produced water, deck drainage and miscellaneous processing wastes are discharged from this platform. The assumed capacity of the accommodation platform during production is 50 personnel. All sewage, domestic and miscellaneous wastes are discharged from this platform.

TABLE 7-1

ASSUMPTIONS FOR SCOTIAN SHELF PRODUCTION SCENARIO

Parameter	Units	Typical Value	Ref.
Field size	10^9 m^3 (10^{12} ft^3)	85(3.0)	(6)
Production rate	gas: 10^6 m^3/d (10^6 ft^3/d) condensate: m^3/d (bbl/d)	11(400) 1000(6000)	(2,3,4)
Well flow rate	10^6 m^3/d (10^6 ft^3/d)	max: 0.4(15) typical: 0.3(10)	(1,4)
Platform type		steel jacket, fixed	(1,4)
Platform configuration, number		3 connected platforms 1 wellhead 1 processing 1 accommodation	(5)
Number of wells (production)		40	(1)
Number of people on platforms		150 during drilling 50 during production	(4) (5)
Characteristics of gas		sweet (no sulphur), moderately wet (considerable condensate)	
Offshore storage		none	
Transportation of product		single dense-phase pipeline to shore	
Shore support		gas processing plant	(4)
Typical well depth	m	6000	(6)
Areal extent of reservoir	km^2	20	(5)

Production rate: Volume of gas produced each day, on surface and following water and condensate removal.

Well flow rate: Volume of gas and other fluids (condensate, water) brought to surface each day through one well.

Sources:

(1) Estimate based on synthesis of offshore production practice in U.S. and U.K. and discussions with Canadian industry personnel.

(2) Anon. 1982a

(3) Anon. 1982b

(4) Thorne, Stevenson and Kellogg 1981

(5) Mobil Oil Canada Ltd. 1982

(6) Anon. 1983

1.3 Grand Banks

An oil field is located under the northeast portion of the Grand Banks, 320 km southeast of St. John's, Newfoundland. The water depth is approximately 80 m. The field has an estimated recoverable reserve of 240 million m^3 (1.5 billion bbl) of crude oil.

The design oil production rate is assumed to be 32,000 m^3/d (200,000 bbl/d). Accurate estimates of produced water volumes are not available. Estimates presented in Section 3 of this chapter are based on world experience with offshore production.

Oil production is from four clusters of ten wells each (30 producing, 10 injection in total) and is tied into a single platform (either bottom-founded gravity or floating) through seafloor fluid pipelines. These wells are drilled over a period of 3 years. The platform contains the well-head for all four clusters, a processing facility for treatment of crude oil and accommodation for all offshore personnel, assumed to number 250. All drilling wastes, produced water, processing wastes and minor wastes such as deck drainage, sewage, cooling water and desalinator wastes are discharged from this single platform. For the purpose of evaluating the overlap of waste discharge zones of influence (Chapter 8), two integrated platforms, each servicing 40 wells, are assumed to be situated 8 km apart.

Transportation of crude oil from the production site to land is by shuttle tanker or by pipeline. Storage is provided on-site in moored semi-submersible tanks for quantities of oil sufficient to fill one large oil tanker. Total offshore storage capacity is 160,000 m^3. Tankers have segregated ballast. Loading of tankers is through a single-point mooring system. The pipeline option requires only about 1-day production storage capacity (32,000 m^3).

TABLE 7-2

ASSUMPTIONS FOR GRAND BANKS PRODUCTION SCENARIO

Parameter	Units	Typical Value	Ref.
Field size	10^6 m^3 (10^6 bbl)	240(1500)	(1,2)
Production rate	m^3/d (bbl/d)	32,000(200,000)	(1,2)
Well flow rate	m^3/d (bbl/d)	max: 2400(15,000) typical: 1600(10,000)	(1,2)
Platform type		fixed or floating	(1)
Platform configuration, number		one, containing wellhead, processing and accommodation	(1,3)
Number of wells		total of 40 30 producing 10 injection	(1,2)
Number of people on platforms		250	(1)
Characteristics of oil/gas		oil with little associated gas and condensate	(2)
Offshore oil storage	m^3 (bbl)	160,000(1,000,000) none	(1)
Transportation of product		Shuttle tanker or pipeline to shore; deep-sea tanker	(1)
Shore support		no information available	
Typical well depth	m	3000	(2)
Areal extent of reservoir	km^2	100	

Production rate: Volume of crude oil produced each day, on surface, following water removal.

Well flow rate: Volume of all fluids brought to surface each day through one well.

Injection well: A well used for injecting water or gas into the formation to increase oil recovery

Sources:

(1) Estimate based on synthesis of offshore production practice in U.S. and U.K. and discussions with Canadian industry personnel.

(2) Handyside and Chipman 1982

(3) Leblanc 1980.

1.4 Beaufort Sea

An oil field is located approximately 40 km offshore from the Mackenzie Delta islands. The water depth is approximately 20 m. The field has an estimated recoverable reserve of 160 million m^3 (1 billion bbl).

The design oil production rate for the field is assumed to be approximately 32,000 m^3/d (200,000 bbl/d). Accurate estimates of produced water volumes are not available. Estimates given in Section 3 of this chapter are based on world experience and information presented in Dome Petroleum Limited et al., Volume 2 (1982).

The ice conditions in the Beaufort Sea dictate that a modified artificial island, caisson-retained island or some other structure capable of withstanding ice forces be used for offshore production facilities. Five well-head island platforms, one of which incorporates produced oil and gas processing facilities and accommodation for 200 offshore personnel, provide the necessary platforms for production. Each well-head platform services 20 wells (13 producing, 7 injection), with the fluids directed by subsea (buried) pipeline to the island containing the processing facilities. The wells are drilled over a period of 3 years. Drilling wastes from 20 wells are discharged from each of the 5 platforms, while produced water, deck drainage, sewage and miscellaneous wastes are discharged from the single processing and accommodation platform.

Storage for 960,000 m^3 (6 million bbl) of crude oil is provided at an island storage and loading terminal. Product is transported by pipeline to shore or by ice-breaking tankers out of the Arctic.

TABLE 7-3

ASSUMPTIONS FOR BEAUFORT SEA PRODUCTION SCENARIO

Parameter	Units	Typical Value	Ref.
Field size	10^6 m^3 (10^6 bbl)	160(1,000)	(1,2)
Production rate	m^3/d (bbl/d)	32,000(200,000)	(1,2)
Well flow rate	m^3/d (bbl/d)	max: 1000(6000) typical: 500(3000)	(2)
Platform type		caisson-retained island	(2)
Platform configuration, number		4 wellhead platforms 1 combined wellhead, processing, accommodation, storage and loading platform	(2)
Number of wells/ platforms		13 producing per island; 7 injection per island	(1,2)
Number of people/ platform		75/platform during drilling	(1)
		200 people on multi-purpose island during production	(1,3)
Characteristics of oil/gas		low sulphur 175 m^3 gas/m^3 oil (1000 cf/bbl)	(3)
Offshore oil storage	m^3 (bbl)	960,000(6,000,000)	(1,2)
Transportation of product		pipeline or tanker (tanker has segregated ballast)	(1,2)
Shore support		no onshore oil processing	(1)
Typical well depth	m	1500	(2,4)
Areal extent of reservoir	km^2	125	(2)

Sources:		
	(1)	Estimate based on synthesis of offshore production practice in U.S. and U.K. and discussions with Canadian industry personnel.
	(2)	Dome Petroleum Limited et al. 1982 (EIS Volume 2)
	(3)	Dome Petroleum Limited et al. 1982 (EIS Volume 4)
	(4)	pers comm. Swiss

2.0 Comparison of Existing Environmental Conditions for Canadian Regions

2.1 Physical Environment

The Scotian Shelf consists of a number of shallow isolated banks cut by a complex of basins and erosional depressions. Commercially viable petroleum hydrocarbon reserves have been identified to date only on the Sable Island Bank. Further description will therefore focus on this particular bank as the most likely site for hydrocarbon production facilities on the Scotian Shelf.

The part of the Bank of interest lies in relatively shallow (32 m) water about 16 km off the eastern end of Sable Island on the Sable Island Bank of the Scotian Shelf. The physical environment of the Bank, winds and sea state, is fairly vigorous with most severe conditions existing between December and January (Martec Ltd.; 1980). The water column on the shallower portions of the Bank is generally well-mixed throughout the year, whereas its structure remains stable from April until the autumn over the deeper parts of the Bank. The mean circulation pattern around Sable Island is clockwise with average residual surface velocities of about 9 cm/sec, maxima about 15 cm/sec and minimum net of 4 cm/sec (Mobil Oil Canada Ltd. unpublished data). Sea ice or icebergs do not occur in this region.

The sedimentary environment around Sable Island is dynamic. Sable Island sand and gravel (<50%) move as sand waves around the island in the same directions as currents. A summer/winter cycle of accretion/erosion exists for sands on Sable Island. Depositional areas are southwest and east of the island and north of the submerged east bar. Sand ultimately moves into deeper waters north, east and south of the Island.

The northeastern portion of the Grand Bank of Newfoundland is an exposed, continental shelf site. Several oil-bearing structures are located in that region within approximately 70 km of the continental shelf break. Water depths in the area of interest range from 75-100 m and fall off to 200 m at the shelf break. The bottom sediment is heterogeneous and includes cobble, lag gravels, coarse sand with some gravel, fine, white sand, and poorly-sorted sands containing silts, clay and gravel. Fines are not generally present at water depths of less than about 120 m (Fader and King 1981). Sand ribbons and waves overlaying gravel deposits are notable and common over the whole of the northern Grand Bank.

The Labrador Current is the predominant hydrographic influence on the northeastern Grand Bank. It flows around the outer perimeter of the shelf, occasionally intruding onto the shelf as far as the area of interest. Mean currents around the Hibernia site flow 185°T and 201°T at 25 and 50 m with velocities of 2.4 and 1.9 cm/s. Within the normal variability of currents at the site are northerly flowing currents of uncertain strength and duration. The variability in the wave and current environment is greatest from October to May. The water column is well-mixed during this period and stratified for the remainder of the year. Pack ice and sea ice do not cover the outer parts of the Grand Bank. Icebergs and smaller ice floes occur in the region during late winter and early spring.

The southeastern Beaufort Sea is a shallow, flat seaward extension of a low coastal plain. The continental shelf extends to the 100 m isobath and may be 150 km wide in some areas. All exploratory drilling to date has occurred shoreward of the 100 m isobath; future offshore production is also expected to be within this area. The nearshore area of the shelf extending from the coastline to the 10 m isobath is approximately 40 km wide off the Tuktoyaktuk Peninsula. Two very important differences between the Beaufort Sea Shelf and the Grand Banks - Scotian Shelf area are almost total coverage of the Beaufort Sea by sea ice for eight to nine months each year and the large freshwater runoff from a single source (Mackenzie River). The presence of sea ice has a profound effect on water circulation and the dynamics of biological populations; in water depths less than 15 m, it is the major agent for seabed sediment workover. The Mackenzie River is the source of about 50% of the mean total annual freshwater discharge and about 95% of the annual particulate loading to the Beaufort Sea Shelf (Thomas et al. 1983). Most of the freshwater and particulate input occurs during the summer freshet period. The strong seasonal variability in river discharge is a prominent cause of large seasonal changes in oceanographic properties of the Beaufort Sea. During the open-water period the water column is highly stratified; at other times the tendency is for an isothermal and isohaline water column to develop. The deposition of sediment generally occurs seaward and eastward of the river mouth. The Mackenzie River discharge plume can be distinguished westward of Herschel Island and as far east as the Amundsen Gulf.

Surface circulation in the southeastern Beaufort Sea tends to be controlled by winds and modified by Mackenzie River outflow. Surface currents rarely exceed 50 cm/s. Near-bottom and mid-water currents appear to be de-coupled from surface winds and are usually variable and weak, seldom exceeding 10 cm/s.

2.2 Biological Resources

The benthic invertebrate community of Sable Island Bank is dominated by sand dollars (Echinarachinus parma) with associated amphipods Unciola irrorata (Stanley and James 1971) and Leptocheirus pinguis. The wave and current regime immediately around Sable Island is sufficient to restrict the benthos to a clam (Tellina agilis) dominated community of isopods and amphipods (Stanley and James 1971; Steele et al. 1979).

The primary demersal fish species of Sable Island Bank are winter flounder (Pseudopleuronectes americanus), yellowtail flounder (Limanda ferruginea), and silver hake (Merluccinus bilinearis) during the summer months. Eggs and larvae of all three species are pelagic, but in the shallows around Sable Island may occur throughout the mixed water column (Jones et al. 1978).

The infaunal benthos in the Grand Banks area is dominated numerically by small polychaete worms (e.g., Exogone hebes and Ophelia limacina). Sand dollars (Echinarachnius parma) and brittlestars (Ophiura robusta) account for the greatest proportion of biomass. A sizable hyperbenthic community of small crustaceans exists on the sandy substrate. The benthic invertebrate community in the area of interest is similar to that occurring on similar substrates over the rest of the Grand Bank. The bottom at deeper depths towards the edge of the shelf becomes progressively finer grained and is occupied by a brittle star community (Hutcheson et al. 1981).

The common demersal fish species on the northeastern Grand Bank are Atlantic cod (Gadus morhua), American plaice (Hippogloissoides platessoides), witch (Glyptocephalus cynoglossus) and yellowtail flounder and sand lance (Ammodytes sp.).

The presence of sea ice in the Beaufort Sea provides a third biological zone - the epontic or ice/seawater interface zone - in addition to the water column (pelagic) and sediment (benthic) zones present at the Grand Banks and Scotian Shelf. Epontic ice communities are important in high latitude ecosystems because, among other reasons, they contribute a significant amount to the total annual production of carbon. Leads in the ice are also important features in the Beaufort Sea ice environment because intense biological activity tends to occur within, and at the margins of the leads. The extremely high seasonal and inter-annual variability in the physical environment of the Beaufort Sea shelf is of great importance because it can determine the availability and abundance of primary food sources (see 2.1 above).

The most important demersal fish in the coastal Beaufort Sea are fourhorn sculpin (*Myoxocephalus quadricornis*), Arctic flounder (*Liopsetta glacialis*) and starry flounder (*Platichthys stellatus*). Offshore, the abundance of demersal fish is generally low. Infaunal benthos are dominated numerically by polychaetes (Thomas and Heath 1983; Thomas *et al*. 1982). Wacasey (1975) has described benthic species abundance and diversity, on the basis of the physical environment, generally corresponding to depth. Benthic community structure appears to be strongly related to substrate and depth (salinity) (Heath *et al*. 1982 a,b).

3.0 Estimate of Future Waste Characteristics and Disposal Practices

Estimates have been prepared for three future Canadian offshore producing areas: Scotian Shelf (gas), Grand Banks (oil) and the Beaufort Sea (oil and gas). The estimates are based on a synthesis of current world practice in offshore production waste handling, as it applies to these Canadian regions. The production scenario for each region (Section 1) provides the basis for the waste estimates. Relevant information on Canadian industry production plans is limited, however, and insufficient to make specific quantitative estimates of waste characteristics and for describing waste treatment and disposal practices. Therefore, the predictions of waste characteristics, treatment and disposal practice in this section draw heavily from Chapters 2, 3 and 4 which review industry practice in the offshore producing areas of the Gulf of Mexico, coast of California, Cook Inlet and North Sea. Factors such as water depth and proximity to shore have been taken into account qualitatively in applying the world-wide review results to the Canadian regions. It has not been possible, however, to quantitatively correlate, for example, North Sea reservoir geology to Grand Banks reservoir geology and use such a correlation to accurately predict the characteristics of produced water for Grand Banks oil production. The waste characteristics and handling practices presented in this section, however, are typical of current world practice under similar producing conditions.

Tables 7-4, 5, 6 and 7 present estimates of typical production waste discharge rates and characteristics (following treatment) and typical waste treatment and disposal practices for the Scotian Shelf, Grand Banks and Beaufort Sea. The estimates are for discharges from a single production platform servicing a number of wells tapping a full gas or oil field (Section 1).

The produced water discharge rates for the Scotian Shelf are based on a typical volume discharge per unit gas produced figure for a gas field having little water inflow. It has been assumed that in this offshore area, high rates of water inflow would indicate serious reservoir problems and would stop economic production. The discharge rates for the Grand Banks and Beaufort Sea assume 0.5 m^3 produced water/m^3 oil production with all discharged to the sea (mid-life of a reservoir) or 1 m^3 produced water/m^3 oil production, with 50 percent reinjected and 50 percent discharged.

The estimates of physical and chemical properties are based on an extensive review of the literature. For most parameters, the chemical characteristics have been assumed to be the same for the three regions. Differences in some parameter values have been made where justified by the site-specific information available. For example, site-specific information on formation waters has not been used to modify these typical estimates for the Scotian Shelf or Grand Banks; no data were available. Limited information on Beaufort Sea formation water characteristics (ESL 1982) did allow some downward modification to the heavy metal values estimated for this region. This approach has been used because a small number of site-specific values, collected during exploration testing, may not be typical of true produced water characteristics and because little site-specific data are available for Canadian regions. The typical values selected for most parameters are considered reliable.

Data for major constituents (major ions and solids) were found to be relatively consistent between regions and the data base is extensive. The oil values in produced water are based on proven treatment unit performance using best practical technology (gas flotation unit) and are consistent over a number of literature sources and geographical regions. The trace organics (aromatics and naphthalenes) are based largely on a number of recent United States studies which are considered to be reliable by industry and government sources. No data were available on trace organics in North Sea produced waters, although they are considered to be relatively high compared to U.S. values (pers. comm. Johnston). The data on heavy metals were found to vary widely between literature sources and geographical regions. The estimates should be considered to be of marginal reliability when applied to a particular Canadian region.

The drilling fluids and cuttings estimates presented are for a single typical well discharging wastes from a well-head platform. Section 1 gives estimates for total number of wells and well-head platform configurations for each region. Estimates of total volume of drilling wastes discharged are given at the end of Table 7-5.

The mud type assumptions and corresponding fluids compositions used are based on current types of mud systems used in each region for exploratory drilling, and on compositions of similar mud systems in the U.S. literature (see Chapter 2). Companies with development plans in the three regions expect similar mud formulations to be used during development drilling, with some changes where required (pers. comm. Tsui; pers. comm. Stobard). Potassium chloride mud systems may be used for formation problems caused by shale swelling, and oil-base mud systems may be required for highly deviated holes, or deep high-temperature zones.

The fluids and cuttings handling methods are based on current offshore practice in the U.S., U.K. and Canada (exploration only).

The fluids and cuttings discharge rates are based on a synthesis of the literature with information available from exploration wells drilled to date in the three Canadian offshore regions. Cuttings and fluid composition estimates, including trace metal contaminant levels, are based on typical values in the literature for similar mud systems rather than specifically on data from exploration wells in Canadian waters.

Low-aromatic (paraffin oil) oil-base mud systems have been assumed as alternatives to water-base mud systems in the lower portions of development wells. While oil-base mud systems may not be used extensively in Canadian waters, (if permitted at all by regulatory authorities), diesel-base muds have gained considerable acceptance in the North Sea for development drilling and are being tested occasionally in U.S. exploration and development drilling. More recently (1982), paraffin oil muds have been tested in the North Sea. It has been assumed that paraffin-base muds will be used rather than diesel-base muds in Canadian waters and that all oil muds will not be discharged, but will be hauled to shore (or to another well) and re-used, as in the U.K. and U.S. Drill cuttings from the use of these mud systems are assumed to be discharged to near the sea bottom, following high efficiency cleaning to removal oil, or are hauled back to shore for disposal.

The estimates for ballast water and storage displacement water handling practice, discharge rates and characteristics are based on North Sea experience assuming current best practical treatment (gas flotation). Neither oily water source will be found at the gas producing installation on the Scotian Shelf. For the Grand Banks and Beaufort Sea oil producing areas, it has been assumed that offshore storage of crude oil (with the attendant storage displacement water) and offshore loading of tankers (with the possibility of tanker ballast being handled) will be carried out. It is probable that, following MARPOL Convention requirements for tankers to have segregated ballast tanks, ballast water will not be handled at offshore loading installations, except where crude oil tankers have had to take on ballast in emergency situations.

TABLE 7-4

ESTIMATE OF TYPICAL CHARACTERISTICS, TREATMENT AND DISPOSAL PRACTICE PRODUCED WATER

	Scotian Shelf	Grand Banks	Beaufort Sea
Discharge rate (m^3/d)	65[1]	16,000	16,000
(bpd)	400	100,000	100,000
Change over time	little; water inflow may make field uneconomical	initially 0 + 10 y 1,600 m^3/d + 20 y 16,000 m^3/d	initially 0 + 10 y 1,600 m^3/d + 20 y 16,000 m^3/d
Treatment method	no treatment (limited oil with produced water) if combined with processing wastes, gravity separator for oil removal	settling tank or surge tank (to plate coalescer) to gas flotation unit	settling tank or surge tank (to plate coalescer) to gas flotation unit
Disposal method	discharge to surface	skim pile to mid-water depth	outfall to mid-water depth
Physical properties			
density (g/cm^3)	1.1	1.1	1.1
temperature (°C)	40	40	40
Chemical composition			
pH	7	7	7
total dissolved solids (mg/L)	100,000	100,000	100,000
suspended solids (mg/L)	1	1	50
chloride (mg/L)	50,000	50,000	50,000
sulphate[2] (mg/L)	0-400[4]	0-400[4]	0-400[4]
sodium (mg/L)	30,000	30,000	30,000
calcium (mg/L)	2,500	2,500	2,500
strontium (mg/L)	300	300	300
total organic carbon (mg/L)	N/A[2]	300	300
oil and grease (IR) (mg/L)	N/A[2]	40	40
oil and grease (GR) (mg/L)	25[3]	35	35
benzene (mg/L)	3.5	3.5	3.5
toluene (mg/L)	2.5	2.5	2.5
xylene (mg/L)	0.5	0.5	0.5
ethylbenzene (mg/L)	0.3	0.3	0.3
naphthalene (mg/L)	0.1	0.1	0.1
2,4-dimethylphenol (mg/L)	0.1	0.1	0.1
phenol (mg/L)	1.0	1.0	1.0
cadmium (mg/L)	0.03	0.03	0.01
chromium (mg/L)	0.02	0.02	0.01
copper (mg/L)	0.1	0.1	0.1
lead (mg/L)	0.1	0.1	0.01
nickel (mg/L)	0.1	0.1	0.1
zinc (mg/L)	0.2	0.2	0.1
mercury (mg/L)	N/A[2]	N/A[2]	0.0002

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[1] Based on 1 bbl produced water/MMSCF gas (5.7 m^3/10^6 m^3), a typical level for well-operated gas field)

[2] Insufficient data in the literature to estimate a typical value.

[3] No data available on oil and grease in produced water from gas platform. Assumes treatment of processing wastes.

[4] Normal condition would be 0 sulphate; if breakthrough of injection water occurs, high sulphate values may result.

TABLE 7-5

ESTIMATE OF TYPICAL CHARACTERISTICS, TREATMENT AND DISPOSAL PRACTICE DRILLING FLUIDS AND CUTTINGS

		Scotian Shelf		Grand Banks		Beaufort Sea	
1.	**Basic Assumptions**						
	well depth	6000 m		3000 m		1500 m	
	angle of deviation	40°		40°		40°	
2.	**Mud Type**	**Interval (m)**	**Type**	**Interval (m)**	**Type**	**Interval (m)**	**Type**
A.	surface	0 - 300	seawater, drill solids, XC polymer	0 - 300	seawater, drill solids, XC polymer	0 - 600	KCl bentonite
B.	mid-depth water-base	300 - 1500	seawater, polymer, KCl	300 - 1500	seawater, polymer, KCl	600 - 1500	freshwater, XC polymer
C.	deep water-base	1500 - 6000	high-density freshwater chrome lignosulfonate	1500 - 3000	medium-density freshwater chrome lignosulfonate	-	-
D.	oil-base[1]	1500 - 6000	low-aromatic	1500 - 3000	low-aromatic	600 - 1500	low aromatic
3.	**Treatment Method**	water-base:	segregation of fluids and cuttings; no treatment	water-base:	segregation of fluids and cuttings; no treatment	water-base:	segregation of fluids and cuttings; no treatment
		oil-base:	cuttings cleaning to reduce oil content (to 1% oil if technology available)	oil-base:	cuttings cleaning to reduce oil content (to 1% oil if technology available)	oil-base:	cuttings cleaning to reduce oil content (to 1% oil if technology available)
4.	**Disposal Method**	water-base mud and cuttings discharged directly to surface; oil-base mud hauled to shore and recycled; oil-base cuttings shunted to sea floor[2]		water-base mud and cuttings discharged directly to surface; oil-base mud hauled to shore and recycled; oil-base cuttings shunted to sea floor[2]		water-base mud and cuttings diluted 25:1 and discharged to surface; oil-base mud hauled to shore and recycled; oil-base cuttings shunted to sea floor[2]	
5.	**Discharge Rate**	**Fluid**	**Cuttings**	**Fluid**	**Cuttings**	**Fluid**	**Cuttings**
	Continuous Mud A	90	40	90	40	60	30
	Mud B	20	30	20	30	15	20
	Mud C	8	6	8	7	N/A[4]	N/A[4]
	(m^3/d) Mud D	N/A[3]	6	N/A[3]	7	N/A[3]	20
	Bulk Mud A	100 m^3 once	N/A[5]	100 m^3 once	N/A[5]	40 m^3 2X	N/A[5]
	Mud B	100 m^3 once	N/A[5]	100 m^3 once	N/A[5]	200 m^3 4X	N/A[5]
	Mud C	100 m^3 6X	N/A[5]	100 m^3 6X	N/A[5]	N/A[4]	N/A[4]
	(m^3) Mud D	N/A[3]	N/A[5]	N/A[3]	N/A[5]	N/A[3]	N/A[5]
6.	**Cuttings Composition**						
	density (g/cm^3)	1.7		1.7		1.5	
	percent solids (wt)	77		77		70	
	percent liquid (wt)	23		23		30	
	oil on cuttings						
	wt% (water-base mud[6])	0-5		0-5		0-5	
	wt% (oil-base mud[7])	5-10		5-10		5-10	
	aromatic content						
	wt% (water-base mud[6])	0-1.5		0-1.5		0-1.5	
	wt% (oil-base mud[7])	1.5		1.5		1.5	
	metals: cadmium (mg/L)	1.5		1.5		1.5	
	chromium (mg/L)	30		30		30	
	mercury (mg/L)	0.05		0.05		0.05	

TABLE 7-5 (continued)

ESTIMATE OF TYPICAL CHARACTERISTICS, TREATMENT AND DISPOSAL PRACTICE
DRILLING FLUIDS AND CUTTINGS

	Scotian Shelf	Grand Banks	Beaufort Sea
7. Drilling Fluid Composition (Whole Mud)			
Mud A:			
pH	9.7	9.7	9.0
density g/cm^3 (lb/gal)	1.1 (9.2)	1.1 (9.2)	1.2 (9.7)
percent solids (wt)	9	9	10
bentonite (wt percent)	8	8	5
barite (wt percent)	0	0	6
caustic soda (NaOH) (wt percent)	0.6	0.6	0.2
potassium chloride (wt percent)	0	0	1.5
XC polymer (wt percent)	0.3	0.3	0
Mud B, C(8):			
pH	12.5	11.5	9.0
density g/cm^3 (lb/gal)	2.1 (17.4)	1.5 (12.7)	1.3 (10.5)
percent solids (wt)	40	20	25
bentonite (wt percent)	6	2	8
barite (wt percent)	29	16	14
caustic soda (NaOH) (wt percent)	1.5	0.5	0.2
potassium chloride (wt percent)	0	0	2
chrome lignosulphonate (wt percent)	1.1	0.5	0.2 (9)
lignite (wt percent)	0.8	0.4	0.1
XC polymer (wt percent)	0	0	0.5
cellulose polymer (wt percent)	0.2	0.1	0
sodium carbonate, bicarbonate (wt percent)	0.4	0.04	0.2
oil content - max. (wt percent)	0.5	0.5	0.5
cadmium(10) (mg/L)	8	6	1.5
chromium(10) (mg/L)	190	125	80
lead(10) (mg/L)	180	275	80
mercury(10) (mg/L)	0.04	0.03	0.03
zinc(10) (mg/L)	230	180	130
8. Total Discharge (One well)			
drilling fluid[11] (m^3)	3,100	2,200	1,200
cuttings[11] (m^3)	1,500	800	300
9. Total Discharge (one well-head platform)			
number of wells	40	40	20
drilling fluid (m^3)	124,000	88,000	24,000
cuttings (m^3)	60,000	32,000	6,000
10. Total Discharge (whole field)			
number of platforms	3	2	5
drilling fluid (m^3)	372,000	176,000	120,000
cuttings (m^3)	180,000	64,000	30,000

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1 Low-aromatic oil-base mud used in place of water-base deep-well mud, if formation problems required; worst-case situation with oil-base mud used over entire mid and deep hole.

2 Oiled cuttings may be alternatively hauled to shore.

3 Oil-base mud (Mud D) not discharged to sea.

4 No deep water-base mud (Mud C) for Beaufort; shallow well depth.

5 Cuttings not discharged in bulk.

6 Maximum contamination of cuttings with formation oil and from use of spotting oil; most of time, cuttings have little or no oil.

7 Assumes a low-aromatic (paraffin-base) oil mud used.

8 Mid-depth mud (B) for Beaufort Sea; deep mud (C) for Scotian Shelf, Grand Banks

9 Ferrochrome instead of chrome lignosulphonate.

10 Metal values based on literature values for whole mud of similar type.

11 Based on continuous and bulk discharge rates and typical days for each mud use.

TABLE 7-6

ESTIMATE OF TYPICAL CHARACTERISTICS, TREATMENT AND DISPOSAL PRACTICE BALLAST AND STORAGE DISPLACEMENT WATER

	Scotian Shelf	Grand Banks	Beaufort Sea
BALLAST WATER			
Storage capacity (m^3)	N/A[1]	0 - 150,000[2]	0 - 150,000[2]
Treatment method	N/A	plate coalescer plus gas flotation unit	plate coalescer plus gas flotation unit
Discharge rate (m^3/d)	N/A	0 - 50,000[2]	0 - 50,000[2]
Disposal method	N/A	surface discharge	surface discharge
Total oil (mg/L)	N/A	10	10
Total aromatics (mg/L)	N/A	5	5
Total dissolved solids (mg/L)	N/A	5,000 - 30,000	5,000 - 30,000
STORAGE DISPLACEMENT WATER			
Storage capaity (m^3)	N/A[1]	160,000	960,000
Treatment method	N/A	plate coalescer (interface water only)	plate coalescer (interface water only)
Disposal method	N/A	surface discharge	surface discharge
Total oil (mg/L)	N/A	10	10
Total aromatics (mg/L)	N/A	trace	trace
Total dissolved solids (mg/L)	N/A	same as seawater	same as seawater

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[1] Not applicable. Gas producing field, with condensate transported directly to shore via pipeline.

[2] International shipping convention requiring segregated ballast may mean that no ballast water is handled offshore; however, small tankers may not have segregated ballast or cross-contamination of tanks may cause oily ballast to be handled offshore.

TABLE 7-7

ESTIMATE OF TYPICAL CHARACTERISTICS, TREATMENT AND DISPOSAL PRACTICE
MINOR OFFSHORE WASTES

		Scotian Shelf[1]	Grand Banks[1]	Beaufort Sea[2]
SANITARY WASTE				
Discharge rate	(m^3/d)	4.5	22.5	50
	(kg/d)	4,500	22,500	50,000
Treatment method		extended aeration	extended aeration	extended aeration or rotating biological disk
Disposal method		direct discharge to surface	direct discharge to surface	direct discharge to surface
BOD_5	(mg/L)	30	30	30
Suspended solids	(mg/L)	40	40	40
Coliform bacteria	(no./100 mL)	200	200	200
Residual chlorine	(mg/L)	1.7	1.7	1.7
DOMESTIC WASTE				
Discharge rate	(m^3/d)	7	35	N/A[2]
	(kg/d)	7,000	35,000	N/A
Treatment method		masceration	masceration	N/A
Disposal method		direct discharge to surface	direct discharge to surface	N/A
BOD_5	(mg/L)	195	195	N/A
Suspended solids	(mg/L)	140	140	N/A
Coliform bacteria	(no./100 mL)	N/A	N/A	N/A
Residual chlorine	(mg/L)	N/A	N/A	N/A
DECK DRAINAGE				
Discharge rate				
- rainfall	m^3/cm rain	1,000[3]	2,500[4]	2,500[4]
- washings	m^3/d	2	2	2
Treatment method		settling tank and skim pile	settling tank and skim pile	settling tank and skim pile
Disposal method		surface discharge	surface discharge or sea sump to mid-depth	surface discharge or sea sump to mid-depth
Composition		25-100 mg/L oil; surfactant	25-100 mg/L oil; surfactant	25-100 mg/L oil; surfactant
DESALINATION WASTE				
Discharge rate		20[5]	30[6]	30[6]
Disposal method		surface discharge	surface discharge	surface discharge
Composition		TDS = 2 x seawater same ionic composition	TDS = 2 x seawater same ionic composition	TDS = 2 x sea water; same ionic composition
COOLING WATER				
Discharge rate		500 m^3/d[7]	10,000 m^3/d[8]	10,000 m^3/d[8]
Treatment method		chlorination	chlorination	chlorination
Disposal method		surface discharge	surface discharge	surface discharge
Composition		seawater, T = 20°C 0.5 mg/L residual chlorine	seawater, T = 20°C 0.5 mg/L residual chlorine	seawater T = 20°C 0.5 mg/L residual chlorine

Footnotes

[1] Sanitary waste (0.09 m^3/person-day) segregated from domestic waste (0.14 m^3/person-day grey water).

[2] Sanitary and domestic wastes combined (total flow 0.23 m^3/person-day).

[3] Assumes medium-size gas production platform.

[4] Assumes large production and processing platform.

[5] Based on typical reverse osmosis unit for offshore platform.

[6] Based on 65 m^3/d potable and process water, using distillation.

[7] Production cooling only.

[8] Production, processing, loading terminal cooling.

N/A Not applicable

CHAPTER 7

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CHAPTER 8

ZONES OF INFLUENCE AND BIOLOGICAL CONCERNS FOR CANADIAN OFFSHORE REGIONS

1.0 Receiving Environment Concentrations

1.1 Scotian Shelf

Heavy Metals

Heavy metals such as cadmium, chromium, copper, zinc, lead, nickel and mercury are often present in discharges of drilling fluids, drill cuttings, and produced waters. The distribution and concentration of these metals in waters and sediments of the Scotian Shelf are a function of both natural and anthropogenic inputs from the Nova Scotia mainland and from the major water massess contributing to circulation patterns in the area (Bewers et al. 1976). Anthropogenic influences are minor except in nearshore areas; spatial and temporal variations in concentrations of the heavy metals in the water column, therefore, are a function of changes in the major circulation patterns.

Concentrations of these heavy metals in sea water of the Scotian Shelf are listed in Table 8-1. There have been no determinations of chromium or lead concentrations in this area; consequently, estimates for those metals are based on the most appropriate data available. Concentrations of copper and nickel occur in higher concentrations near the coast, a result probably related to input from natural weathering. The difference in nearshore and offshore concentrations of cadmium are probably not significant, because concentrations are very low, at or near the detection limit of the methods used.

The concentration of heavy metals in the surficial sediments of the Scotian Shelf generally reflects the sediment type. The finer-grained LaHave sediments in the area where Hoffman (1970) sampled contain substantially higher concentrations of heavy metals than the coarser Sable Island sand and gravel and Sambro sand which dominates most of the banks and slope (King 1970; Hawkins 1982). Concentrations of chromium and nickel in the Sable Island and Sambro sands are likely to be lower than those given in Table 8-2. Comparing data from other areas such as the Gulf of St. Lawrence (Loring 1978; Loring 1979), the Bay of Fundy (Loring 1982) and the

TABLE 8-1

CONCENTRATIONS OF SELECTED HEAVY METALS IN SEA WATER OF THE SCOTIAN SHELF

(µg/kg)

METAL		CONCENTRATION	REFERENCE
Cd	nearshore*	0.045	Bewers et al. 1976
	offshore**	0.034	Bewers et al. 1976; Stoffyn 1982
Cr		0.3	Brewer and Spencer 1975
Cu	nearshore*	0.48	Bewers et al. 1976; Hoff 1977
	offshore**	0.24	Bewers et al. 1976; Stoffyn 1982
Pb		0.02	Brewer and Spencer 1975
Ni	nearshore*	0.25	Bewers et al. 1976
	offshore**	0.2	Bewers et al. 1976; Stoffyn 1982
Hg		0.092	Cranston and Buckley 1972
Zn	nearshore*	1.25	Bewers et al. 1975
	offshore**	0.72	Bewers et al. 1975

* mean of values given for "surface shelf" and "deep shelf" waters.

** continental slope

TABLE 8-2

CONCENTRATIONS OF SELECTED HEAVY METALS IN SURFICIAL SEDIMENTS OF THE SCOTIAN SHELF (µg/g)

METAL	CONCENTRATION	REFERENCE
Cd	0.01-0.06	Hawkins 1982; Bothner _et_ _al_. 1980
Cr	130	Hoffman 1970
Cu	5-10 52	Hawkins 1982 Hoffman 1970
Pb	5-15 85	Hawkins 1982 Hoffman 1970
Ni	80	Hoffman 1970
V	85	Hoffman 1970
Hg	0.1	Jonasson and Boyle 1971
Zn	approx. 35-84*	Loring 1978

* estimated from "open" Gulf of St. Lawrence values. Values range from those expected for sand-sized to silt-sized particles.

southeastern U.S. shelf (Bothner et al. 1980), estimates of 60 and 20 µg/g for chromium and nickel, respectively seem to be reasonable for these coarser sediments.

Dissolved and Suspended Solids

There are no data for dissolved and suspended solids for the waters of the Scotian Shelf. Particulate organic carbon concentrations vary seasonally from 15 to 124 mg m^{-3} with highest concentrations occurring in April and July (Gordon 1977). Secchi disc depth data for the area also exhibit strong seasonality, depths ranging from 4 to 12 m with the lowest values occurring in April (pers. comm. O'Boyle). Observations made on the shelf (pers. comm. Bennett; Heffler; and B. Hargrave) indicate that concentrations of suspended particulate material over the sandy banks are low (<1 g m^{-3}); higher concentrations, however, are often observed in some of these areas with maximum concentrations (>10 g m^{-3}) occurring beneath the thermocline. Even higher concentrations (>100 g m^{-3}) have been observed in deep waters of the slope.

Petroleum Hydrocarbons

The concentration of petroleum hydrocarbons in the waters and surficial sediments of the Scotian Shelf has been determined by fluorescence spectrophotometric and gas chromatographic techniques. There has been no determination of concentrations of polycyclic aromatic hydrocarbons in this area.

Concentrations of fluorescing and saturated hydrocarbons are low in the waters and sediments of the Scotian Shelf (see Tables 8-3 and 8-4). The concentrations are similar to those found in other areas of the world. Hydrocarbon concentrations increase and compositional changes occur in water and sediments as the shoreline is approached reflecting the input of anthropogenic and biogenic materials from the land (Keizer et al. 1977; Keizer et al. 1978). Temporal variations in hydrocarbon concentrations and composition in the water column may occur in these nearshore areas as the result of seasonal variations in anthropogenic input (Gordon et al. 1978; Paradis and Ackman 1977).

TABLE 8-3

TYPICAL CONCENTRATIONS OF FLUORESCING HYDROCARBONS IN SEA WATER

REGION	CONCENTRATION (µg/L)	REFERENCE
Scotian Shelf	0.2 - 2.0	Keizer *et al*. 1977
Gulf of St. Lawrence	0.6 - 1.5	Keizer *et al*. 1977
St. Lawrence Estuary	0.4 - 1.1	Keizer *et al*. 1977
Bedford Basin, N.S.	0.2 - 9.8	Gordon *et al*. 1978
South Beaufort Sea	0.05 - 0.3	Wong *et al*. 1976
Ekofisk blowout		
- 1 wk. after	0.8 - 15.2	Mackie *et al*. 1978
- 2 mo. after	< 0.2 - 4.0	

TYPICAL CONCENTRATIONS OF SATURATED HYDROCARBONS IN SEA WATER

REGION	CONCENTRATION (ng/L)	REFERENCE
Scotian Shelf	78 - 154	Keizer *et al*. 1977
Gulf of St. Lawrence	24 - 1,005	Keizer *et al*. 1977
St. Lawrence Estuary	34 - 372	Keizer *et al*. 1977
Sargasso Sea	ND - 145	Keizer *et al*. 1977
Bedford Basin, N.S.	50 - 1,000	Gordon *et al*. 1978
Georges Bank	200 - 1,900	Boehm *et al*. 1979

TABLE 8-4

TYPICAL CONCENTRATIONS OF FLUORESCING HYDROCARBONS IN SURFICIAL SEDIMENTS FROM THE SCOTIAN SHELF AND OTHER LOCATIONS

REGION	CONCENTRATION (µg/L)	REFERENCE
Scotian Shelf	<1 - 94	Keizer et al. 1977
North Sea	1 - 26	Ward et al. 1980
Come-By-Chance, Nfld.	1 - 25	Keizer 1974
Various	5 - 405	Hargrave and Philips 1975

Organic Material

Organic matter in the water column and sediments of the Scotian Shelf is largely biogenic; consequently there is no unusual demand on the dissolved oxygen in the water or surface sediments. Many Nova Scotian coastal communities, however, use the ocean as a disposal site for untreated, or at best, partially treated, sewage and industrial wastes. The cities of Halifax and Dartmouth discharge untreated sewage from approximately 250,000 people into Halifax Harbour along with the effluent from two oil refineries and numerous small industries. Sydney Harbour is the recipient of the untreated waste from a coke plant and steel mill both of which discharge untreated waste into the harbour polluting water and sediments to the extent that fishing is no longer permitted in the area (pers. comm. Scarratt). Numerous small harbours along the coast also receive quantities of either domestic or industrial waste sufficient to affect the quality of water and surface sediments in the immediate area of the input (e.g., Ernst et al. 1982).

1.2 Grand Banks

Heavy Metals

No data have been published on the concentration of heavy metals in the sea water and surface sediments from the Grand Banks. Mobil Oil Canada Ltd. have had samples from the area analysed for heavy metals but these data are not yet in the public domain. Concentrations of heavy metals in sea water over the Grand Banks can be expected to be no higher than those given in Table 8-1 for the offshore areas of the Scotian Shelf. Trace metal concentrations in surface sediments from the Grand Banks are not as easily predicted because they reflect, in part, the source of these sediments. Sediments from Gulf of St. Lawrence and Placentia Bay, Newfoundland (Table 8-5) have similar concentrations of the heavy metals of interest; both of these areas, however, are more exposed to input from terrestrial sources. Surface sediments from the Grand Banks are coarse (Levy 1983) and therefore concentrations of heavy metals can be expected to be equal to or lower than those for the Scotian Shelf (Table 8-2). The deeper channels contain finer sediments which may contain higher concentrations of heavy metals.

TABLE 8-5

CONCENTRATIONS OF SELECTED HEAVY METALS IN FINE SEDIMENTS FROM AREAS NEAR THE GRAND BANKS (µg/g)

LOCATION	Cd	Cr	Cu	Zn	Pb	Ni	V	REFERENCE
Gulf of St. Lawrence	0.26	87	25	~84	21	36	105	Loring 1978, 1979
Placentia Bay	-	46	26	74	28	36	-	Willey 1976

TABLE 8-6

RANGE OF CONCENTRATIONS OF FLUORESCING HYDROCARBONS ON THE GRAND BANKS

Floating particulate oil[1]	0 - 85 µg m^{-2} (2/3 samples were zero)
Surface microlayer*	25 - 50 µg/L
Water column	0.05 - 4.05 µg/L (95% were <1 µg/L)
Bottom sediments	0 - 7.25 µg/g

1 Determination by weight

* Higher concentrations were observed at 3 locations in the Hibernia grid

Source: Levy 1983

Dissolved and Suspended Solids

There are no data available for dissolved and suspended solids concentrations in the waters of the Grand Banks. Concentrations should generally be low (<1 mg L^{-1}) due to the coarse grain of the surface sediments.

Petroleum Hydrocarbons

Concentrations of petroleum-derived hydrocarbons in the water and sediments of the Grand Banks were surveyed by Levy (1983). The data are summarized in Table 8-6; comparison with Tables 8-3 and 8-4 indicates the very low levels of petroleum derived hydrocarbons in the marine environment of the Grand Banks.

Organic Material and Toxicants

There are no data available for the concentration of either dissolved or particulate organic matter or various toxicants in the water and sediments of the Grand Banks. Due to the remoteness from any major population or industrial centres, its is unlikely that any abnormal levels would be observed. The concentration of organic matter in the water column will reflect biological production while sediment organic matter concentration is negatively-correlated with sediment grain size.

1.3 Beaufort Sea

The Mackenzie River is the dominant source of heavy metals and hydrocarbons to the Beaufort Sea Shelf. Anthropogenic inputs are associated with current oil exploration activities; these are usually limited to very local zones around specific activity areas and are at least three orders of magnitude lower than natural inputs (Thomas and Macdonald 1983). The water and particulate river inputs are highly seasonal in nature; this can lead to large spatial and temporal differences in the distribution of dissolved heavy metals on the Beaufort Sea Shelf.

Heavy Metals

Typical concentrations of dissolved chromium, iron, nickel, copper, zinc, cadmium, mercury and lead are given in Table 8-7. With the exception of the data given by Erickson et al. 1982, which were collected over a 15-month period, all other data were collected over very short time periods, typically days to weeks. In all cases, the data are representative of concentrations at specific locations; no synoptic regional data for dissolved heavy metals in the Beaufort Sea exist.

Typical concentrations of heavy metals in the surficial sediments of the Beaufort Sea are shown in Table 8-8. There is a high correlation between sediment grain size and sediment trace metal composition. Sediments composed chiefly of sand-sized particles usually contain relatively low concentrations of iron and trace metals when compared to sediments consisting of silt or clay-sized particles which are usually rich in iron and other metals. There is a strong regional variation in the sediment grain-size distribution on the Beaufort Sea Shelf inside the 100-m isobath (Pelletier 1976) and a similar regional variation in the distribution of heavy metals in surficial sediments. The range of concentration in shelf sediments for each of Fe, Cu, Zn, Cd, Ni, Cr, Pb and Hg may exceed an order of magnitude.

Hydrocarbons

The concentrations of various hydrocarbon compounds measured in the waters and sediments of the Beaufort Sea are given in Table 8-9. The concentrations of polycyclic aromatic hydrocarbons (PAH) in the waters of the southern Beaufort Sea vary from 13 to 45 ng/L (chrysene equivalents), and vary inversely with salinity (Wong et al. 1976). PAH concentrations in nearshore waters are much more variable than PAH in deeper water, possibly influenced by the Mackenzie River which flows through regions with known fossil fuel deposits and natural seepages.

Wong et al. (1976) reported that the distribution of n-paraffins in marine sediments of the southern Beaufort Sea was characteristic of sediments containing both marine and terrestrial biological and detrital materials. All sediments contained as series of n-paraffins (n-C_{17} to n-C_{32}), the isoprenoids pristane and phytane, and an unresolved group of non-polar hydrocarbons (envelope). The concentration of the n-paraffins was 2.6 to 23.6 µg/g, while levels of the unresolved envelope hydrocarbons varied from 28.3 to 136.7 µg/g. Peake et al. (1972) reported a range of 1.23 to 9.40 µg/g for n-paraffins in ten Beaufort Sea sediments. Wong et al. (1976) noted that an

TABLE 8-7

CONCENTRATIONS OF HEAVY METALS IN SEA WATER OF THE BEAUFORT SEA

METAL	UNITS	SAMPLING LOCATION	CONCENTRATION		NUMBER OF SAMPLES	REFERENCE
			Range	Mean		
Cr	µg/kg	12 Dome Drillsites	0.01 - 0.40	0.07	55	Thomas 1978a
		Netserk/Isserk	2 - 4	2.18	11	Beak 1978
		Issungnak O-61	0.09 - 0.20	0.15	52	Erickson et al. 1982
Fe	µg/kg	12 Dome Drillsites	1 - 213	40	55	Thomas 1978a
Ni	µg/kg	Tarsiut A-25	0.37 - 1.03	0.73	9	Thomas 1978b
		Kilannak A-77	0.32 - 1.59	0.72	17	Thomas 1979a
Cu	µg/kg	12 Dome Drillsites	0.1 - 3.5	0.73	55	Thomas 1978a
		Issungnak O-61	0.35 - 1.08	0.51	54	Erickson et al. 1982
Cd	µg/kg	12 Dome Drillsites	0.01 - 0.12	0.05	55	Thomas 1978a
		Issungnak O-61	0.03 - 0.12	0.06	54	Erickson et al. 1982
Hg	µg/kg	12 Dome Drillsites	0.001 - 0.092	0.018	56	Thomas 1978a
		Issungnak O-61	0.003 - 0.022	0.021	35	Erickson et al. 1982
		Beaufort Sea (Tuk. Penin. area)	0.004 - 0.034	0.011	39	DFO 1975
Pb	µg/kg	12 Dome Drillsites	< 0.02 - 0.57	j0.15	55	Thomas 1978a
		Netserk/Isserk	< 2 - 4	2.15	33	Beak, 1978

TABLE 8-8

CONCENTRATIONS OF HEAVY METALS IN BEAUFORT SEA SEDIMENTS

METAL	UNITS (dry weight basis)	SAMPLING LOCATION	CONCENTRATION		NUMBER OF SAMPLES	REFERENCE
			Range	Mean		
Cr	µg/g	12 Dome Drillsites	13 - 156	83	144	Thomas 1978a
		Various (Beaufort Sea Project)	8 - 44	27	61	DFO 1975
		Tuk Harbour/McKinley Bay	21 - 78	50	47	Thomas 1979b
		Issungnak O-61	3 - 23	13	60	Beak 1981
		Issungnak O-61	47 - 146	113	18	Erickson *et al.* 1982
Fe	%	12 Dome Drillsites	2.08 - 5.12	3.88	144	Thomas 1978a
		Various (Beaufort Sea Project)	2.44 - 4.24	3.29	60	DFO 1975
		Tuk Harbour/McKinley Bay	0.95 - 4.58	3.24	47	Thomas 1979b
Ni	µg/g	Tarsiut A-25	86 - 119	100	20	Thomas 1979a
		McKinley Bay/Tuk Harbour	< 1 - 35	23	47	Thomas 1979b
Cu	µg/g	12 Dome Drillsites	14 - 37	26	144	Thomas 1978a
		Various (Beaufort Sea Project)	21 - 101	32	61	DFO 1975
		McKinley Bay/Tuk Harbour	3.8 - 40	28	47	Thomas 1979b
		Issungnak O-61	11 - 31	24	18	Erickson *et al.* 1982
Zn	µg/g	12 Dome Drillsites	17 - 142	107	144	Thomas 1978a
		Various (Beaufort Sea Project)	94 - 191	150	60	DFO 1975
		McKinley Bay/Tuk Harbour	28 - 157	112	47	Thomas 1979b
		Issungnak O-61	50 - 168	121	18	Erickson *et al.* 1982
Cd	µg/g	12 Dome Drillsites	< 0.2	< 0.2	144	Thomas 1978a
		Various (Beaufort Sea Project)	0.11 - 0.83	0.29	60	DFO 1975
		McKinley Bay/Tuk Harbour	< 0.2	< 0.2	47	Thomas 1979b
		Issungnak O-61	0.15 - 0.40	0.25	18	Erickson *et al.* 1982
Hg	ng/g	12 Dome Drillsites	28 - 114	73	144	Thomas 1978a
		Various (Beaufort Sea Project)	29 - 109	65	34	DFO 1975
		McKinley Bay/Tuk Harbour	32 - 179	96	47	Thomas 1979b
		Issungnak O-61	10 - 114	68	60	Beak 1981
		Issungnak O-61	35 - 180	88	16	Erickson *et al.* 1982
Pb	µg/g	12 Dome Drillsites	< 3 - 14	4.2	144	Thomas 1978a
		Various (Beaufort Sea Project)	3 - 7.5	6	41	DFO 1975
		Issungnak O-61	6.5 - 28.8	22.4	60	Beak 1981

TABLE 8-9

CONCENTRATIONS OF HYDROCARBONS IN THE SEA WATER AND SEDIMENTS OF THE BEAUFORT SEA

MEDIUM SAMPLED	NO. OF SAMPLES	HYDROCARBON GROUP/COMPOUND	CONCENTRATION UNITS	CONCENTRATION RANGE	REFERENCE
Sea Water	10	polyaromatic hydrocarbons	ng/L (chrysene equivalents)	13 - 45	Wong et al. 1976
Sediment	29	(a) n-paraffins (b) unresolved hydrocarbons (c) total hydrocarbons	µg/g dry weight	(a) 2.6 - 23.6 (b) 15.8 - 150.3 (c) 18.4 - 163.6	Wong et al. 1976
Sediment	20	n-paraffins + pristane + phytane	µg/g dry weight	0.1 - 12.5	Shaw 1977
Sediment	18	polyaromatic hydrocarbons (sum of benzanthracene, chrysene, pyrene, perylene, and certain other isomers)	µg/kg wet weight	236 - 984	Wong et al. 1976
Sediment (marine)	22	polyaromatic hydrocarbons (sum of benzanthraene, chrysene, pyrene, perylene, and certain other isomers)	µg/kg wet weight	97 - 1341	Wong et al. 1976
Sediment (near-shore)	10	polyaromatic hydrocarbons (pyrene & benzo(a)pyrene + perylene + coronene)	µg/kg dry weight	0.4 - 20	Wong et al. 1976
Sediment	27	benzpyrene	µg/kg dry weight	0.2 - 33	Stich and Dunn 1980
Sediment	12	total resolved PAH	µg/kg dry weight	68 - 1856	Erickson et al. 1982
Sediment	12	total aliphatic hydrocarbons	µg/g dry weight	1.3 - 80.3	Thomas et al. 1982

odd-carbon predominance, which is characteristic of terrestrial plant material, was evident in most of their marine sediment samples from the Beaufort Sea, suggesting an influx of detritus from the Mackenzie River.

Wong et al. (1976) also reported that total PAH (defined as the sum of chrysene, benzanthracene, perylene, phenanthrene, pyrene and certain other isomers) in marine sediments from the Beaufort Sea ranged from 97 to 1340 µg/kg wet weight basis. Total UV-PAH (defined as the sum of pyrene, benz(a)pyrene, perylene and coronene) was 0.4 to 20.0 µg/kg dry weight for nearshore sediments and about 300 µg/kg dry weight for benthic sediments. In a subsequent study, Stich and Dunn (1980) measured about 0.5 to 3.3 µg/kg dry weight benz(a)pyrene in 20 sediment samples from the southern Beaufort Sea. The sediments of the Beaufort Sea appear to contain an elevated PAH baseline relative to global background levels. The most likely source of the high natural PAH baseline is the Mackenzie River which, as noted earlier, flows through regions with known fossil fuel deposits, natural seepages and burned-over areas, all of these being naturally occurring sources of polycyclic aromatic hydrocarbons.

2.0 Dispersion Model

The primary objective of the modelling procedure used in this study was to provide a basis for comparing the relative dispersion characteristics (relative zones of influence) of the Scotian Shelf, Grand Banks and the Beaufort Sea taking into account the oceanographic data available for each region. A new model that would quantitatively predict concentrations of contaminants in sea water and sediments under very specific environmental conditions was not developed, as such a large undertaking was outside the scope of the present work.

Instead a simple model was chosen (see Section 2.2) which was adequate for the purpose given the constraints of a very limited data base; there is a poor understanding of the circulation patterns in specific regions of each offshore area especially in terms of vertical water-column structure and short-term and long-term variability. Complicated models are described in the literature and could have been adapted to regions such as the Grand Banks, Scotian Shelf and Beaufort Sea. There is little advantage to their use, however, because the output data would be severely restricted by the lack of detailed input data.

2.1 The Application of Models to the Dispersion of Production Wastes in Marine Environments

The ultimate goal of modelling is to provide a quantitative predictive capability to a specific disposal scenario. There can be considerable utility in models, however, which provide qualitative information by defining general features and zones of influence. The assembling of accurate models showing production waste disposal at sea is difficult because of the complexity of the receiving waters and the wastes themselves. Production wastes from offshore oil and gas development are varied in their physical and chemical properties and in their mode of discharge. Analogies for the dispersion and fate of production wastes in the marine environment exist elsewhere and numerous models have been developed to describe the fate of marine discharges. Attempts to model production waste disposal have, therefore, utilized various models from other applications, with the necessary modifications.

Modelling of offshore production wastes has thus far been concerned almost exclusively with the disposal of drilling fluids and cuttings. Field studies of drilling fluid disposal have revealed the following general characteristics (Neff 1982):

1) initial dilution is rapid; some dilution occurs within a submerged discharge pipe and initial convective mixing in the vicinity of a drilling rig is substantial

2) two plumes are formed in deep water (> 20 m):

   i) an upper plume visible at the surface comprising very fine suspended particulates which separate from the bulk of the discharge during initial mixing and;

   ii) a lower plume containing the bulk of material which descends rapidly until it reached the bottom or a point of neutral density (cuttings tend to fall rapidly to the bottom).

3) drilling fluid plumes, as defined by light transmittance or suspended solids are diluted rapidly and are short lived; background conditions are attained generally within 1000 m of discharge

The models that have been developed to account for these features have had varying degrees of success. A comparison of the main drilling fluid discharge models used to date is given in Table 8-10.

Dames and Moore (1978) used several models to describe the dispersion of drilling fluids and cuttings discharged at a C.O.S.T.* well in Cook Inlet, Alaska. Dispersion was modelled by considering the cuttings and mud separately. Cuttings dispersal was assumed to be governed by current velocity and the settling velocities because of the high density and relatively coarse nature of the particles. A mathematical model was developed around these assumptions to describe the sediment particle flux and particle size distribution. The mud portion was modelled in three ways. Initial dilution was modelled on the basis of a jet discharge in deep water (Fan 1967) neglecting any effects of the drilling rig or flow fields. The second approach assumed that current flow past the drilling rig produces a wake. Since drilling fluids were discharged above the keel of the semi-submersible, they would be discharged into the wake and could therefore be transported in accordance with wake dispersion. The third model dealt with the dispersion of the mud plume on the surface (assuming the plume to be slightly buoyant because of freshwater content and temperature). The model was based on one developed by Shirazi and Davis (1974) to describe thermal plumes.

The models were field tested using two bulk discharges (one of active drilling mud; the other a sand trap discharge) and one continuous discharge. The discharge

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* Continental Offshore Stratigraphic Test

TABLE 8-10

COMPARISON OF DRILLING FLUID DISCHARGE DISPERSION MODELS

MODEL	REFERENCE	APPLICATION	FIELD TEST	TYPE OF DISCHARGE & LOCATION	PREDICTIVE CAPABILITY
Jet	Fan (1967) Dames & Moore 1978	Initial dilution from submerged pipe	Yes	Bulk (2 types) Continuous: Cook Inlet (64 m)	Model grossly underestimates initial dilution by factor of 100 or more.
Wake Dispersion	Dames & Moore 1978	Passive lateral dispersion of surface plume in wake of drilling rig.	Yes	Bulk: Active Drilling Sand Trap Cook Inlet (64 m)	Linear wake relationship gave accurate predictions of plume width for bulk discharge of active mud system from edge of mixing zone to 6 km. Width of plume of sand trap discharge accurately predicted to 2 km by square root wake relationship. Grossly overestimates plume width beyond that.
Shirazi-Davis	Shirazi-Davis (1974) Dames & Moore (1978)	Passive lateral dispersion of surface plume.	Yes	Bulk: Active Drilling Sand Trap Continuous: Cook Inlet (64 m)	Good prediction of plume width for both bulk discharges to 2 km. Underestimated plume width for active drilling discharge and overestimated for sand trap beyond that. Concentration estimates on basis of Rhodamine dye tracer were slightly high (less than factor of 5). Trend correctly predicted to 7 km.
Cuttings Dispersal	Dames & Moore (1978)	Bottom settling pattern and size distribution of coarse sediment	Yes	Cook Inlet (64 m)	Inconclusive field test: Material on bottom was mobilized after reaching bottom sediment by strong currents.
Under ice jet	Northern Technical Services (1981)	Jet discharge of fluid under ice in shallow water ((< 10 m)	Yes	Bulk: Prudhoe Bay (10 m)	Over estimates plume concentration and sedimentation rate as determined by Rhodamine dye tracing and sediment trap measurements: Gives conservative estimate of wall jet thickness.
Exxon	Brandsma et al (1980)	3 Dimensional analysis of drilling fluid dispersion from submerged pipe.	Yes	Bulk: Gulf of Mexico (23 m)	Gives accurate initial dilution estimates: In nearfield predicts general features: At 100 m: accurately predicted vertical profiles of suspended part. At 30 m: Plume predicted to be 5 m shallower than observed. At 180 - 250 m: Plume predicted to be 5 m deeper than observed. No far field tests.

pipe was 15 m below the surface and the water depth was 64 m. The plume was defined by light transmittance, dye tracking and sedimentation rates (sediment trap deployments). The jet model grossly underestimated the dilution rate in all cases. Predictions from the two other models, assuming a starting point 150 m from the discharge (end of observed mixing zone), were compared with field data for Rhodamine WT dispersal. The Shirazi-Davis model predictions of concentration were high for most tests although qualitative trends were correct (to a distance of approximately 7 km). Plume width predictions by the Shirazi-Davis model were in satisfactory agreement to about 2 km but underestimated plume width beyond that for the active drilling fluid bulk discharge and overestimated plume width for the sand trap discharge. The wake model was able to predict plume width accurately assuming a linear wake relationship out to 6 km for the bulk discharge of active drilling mud. The width of the plume from the sand trap discharge was accurately predicted to a distance of about 2 km by a square-root wake relationship but was grossly overestimated beyond that. Comparison of the cuttings dispersal model with sediment data was complicated by the mobility of bottom sediments. Cuttings had evidently been dispersed and buried after settling to the bottom. Generic simulation of the mud plume was also made by combining empirically based mixing analysis with the Shirazi-Davis model and using this to predict plume concentrations on five different horizontal planes (0-30 m). The predictions were not field tested. The results of these studies indicate that the simple jet model cannot be used to simulate drilling fluid dispersal. The results for the cuttings dispersal model are ambiguous because of the lack of supporting data. The wake and Shirazi-Davis models could be of qualitative use for describing the surface extent of the upper plume in the near field once this has surfaced. Neither model has a long-range quantitative predictive capability. Both models deal only with surface effects; depth dispersion and the dispersal of the lower plume have been ignored.

Northern Technical Services (1980) have modelled the discharge of drilling fluids through ice into shallow water (< 10 m). The process was modelled numerically and physically by means of a laboratory scaled test. The physical model indicated that the plume descends as a radial jet and after hitting the bottom, spreads as a radial wall jet. The mathematical model was formulated on this basis without considering the long-term fate of drilling fluid after the dynamic collapse of the wall jet. The model predictions were field-tested and provided conservative estimates of plume behaviour in the near field. Field data were collected to a distance of 122 m from the discharge point. The plume was traced with Rhodamine dye and the authors suggest that the overestimation of the plume concentrations as predicted by the model may be a result of non-conservative behaviour of the dye through flocculation. The model assumes conservative behaviour of plume constituents.

Brandsma et al. (1980) have developed a 3-D computer model which is more sophisticated and of more general application for drilling fluid dispersal. They assumed that dispersion occurs in three distinct phases:

1) initial convective descent of the material discharged as a jet
2) dynamic collapse when the plume encounters the level of neutral buoyancy or the bottom, and
3) passive diffusion

The first two dynamic phases occur in the near field and are short term. Modelling of this portion of plume evolution was based on the Koh and Chang (1973) model for dumping of dredge spoils and solid wastes. The passive diffusion portion was developed specifically for this model. The authors also added an initial dilution calculation to account for the observation that at low Froude numbers (< 2), pronounced dilution occurs before mud leaves a submerged discharge pipe. Inclusion of this calculation results in increased discharge flow and decreases in bulk density and concentration of solids. The model predictions were compared with field data from a mud dump at a well site in the Gulf of Mexico (23 m depth). Field measurements were made of sedimentation (sediment traps) and suspended solid concentrations to a distance of 250 m from the rig. Vertical profiles of suspended solids were closely predicted at intermediate distances (~100 m). Close to the rig (50 m), however, the model overestimated sedimentation and had the plume about 5 m shallower than observed. At the farthest locations (180-250 m), the model underestimated sedimentation and had the plume centered about 5 m deeper than observed. Initial dilution predictions, however, were in close agreement with observed values and the general behaviour (direction of drift, double plume development) was correctly predicted. The model has not been field-tested for far-field (> 250 m) or long-term predictions; it is still being developed. The authors reported in their 1980 presentation that future work would include effects of the turbulent wake produced by drilling rigs, and a more sophisticated estimation of diffusion coefficients using oceanographic parameters.

The model under development by Exxon (Brandsma et al. 1980) offers the greatest promise for general applicability to drilling mud and cuttings disposal. Using this and the models for the surface plume derived for the C.O.S.T. well in Alaska, good estimates of initial dilutions and qualitative near-field dispersion can be made. Modelling is still very much developmental, however. Empirical evidence suggests that drilling fluid plumes will be effectively dispersed within 1000 m of the discharge point. Definition of the plume in the far field, however, is limited by the sensitivity of measurements used to define it. The validity of far-field and long-term effects of model predictions are difficult to verify and must be viewed at present as informed guesses only.

2.2 Description of Dispersion Model

The model used in this study assumes that dispersion of a substance in water is the result of three separate and independent processes: diffusion, advection, and buoyancy. Diffusion is the process by which a substance, gently introduced to a solution such as sea water, will gradually and evenly spread in three dimensions. The diffusion seen in a still solution in a laboratory beaker is the result of molecular motion and is called molecular diffusion. Molecular diffusion occurs in the ocean, but in view of rate and extent in relation to other processes, it is insignificant. Diffusion in the ocean is seen as primarily the result of turbulence produced by large scale effects of wind and current. The model assumes that turbulent and molecular diffusion follow the same relationship and can be expressed in terms of a diffusion coefficient representing a rate of spread in distance squared per unit time.

Advection is the process in which a substance is transported in one or more directions by fluid motion e.g., a current. Advection affects a solid object placed in the fluid environment. In the oceans advection is pronounced, and may spread a substance many kilometres from the point at which it was introduced.

Buoyancy affects a mass placed in a fluid by nature of the difference in density between the mass and the fluid. The mass may be a fluid or a solid and can be positively or negatively buoyant, i.e., less dense or more dense than the fluid it displaces.

The model combines diffusion, advection and buoyancy in a single equation imposed on a fixed Eulerian grid. It is assumed that upon discharge a substance forms an initial cloud of finite dimensions X_0, Y_0 and Z_0. The cloud begins immediately to diffuse in the X, Y and Z directions, but at the same time it is transported in the X, Y or Z direction by advection and buoyancy. Diffusion is parameterized by a diffusion coefficient for the X and Y directions and a separate and smaller (by 10^{-3}) coefficient for the Z direction. The rate of vertical diffusion in the ocean is observed to be considerably smaller than the horizontal diffusion due to the inhibiting effect of vertical density stratification. Advection in the horizontal direction is expressed in the form of current and tidal velocities. Buoyancy is represented by sinking rates (for particles and dense materials) or rising rates (for oil droplets).

Once the dispersion process begins, the cloud produced by the initial discharge moves out along and throughout the grid, producing concentrations of the discharged substance at each grid point X_a, Y_b, Z_c. Successive or continuous discharges will produce additional clouds which will move through the same grid points adding to the previous concentration. The model superimposes successive clouds on each set of grid points, at preselected time increments, for the duration of model run. The resulting concentration $C_{x,y,z}$ equals:

$$\frac{M}{8X_oY_oZ_o} \times \left[\mathrm{erf} \left(\frac{X + X_o/2 - X_d}{\sqrt{4D_x t}} \right) - \mathrm{erf} \left(\frac{X - X_o/2 - X_d}{\sqrt{4D_x t}} \right) \right]$$

$$\times \left[\mathrm{erf} \left(\frac{Y + Y_o/2 - Y_d}{\sqrt{4D_y t}} \right) - \mathrm{erf} \left(\frac{Y - Y_o/2 - Y_d}{\sqrt{4D_y t}} \right) \right]$$

$$\times \left[\mathrm{erf} \left(\frac{Z + Z_o/2 - Z_d}{\sqrt{4D_z t}} \right) - \mathrm{erf} \left(\frac{Z - Z_o/2 - Z_d}{\sqrt{4D_z t}} \right) \right]$$

where x, y and z are spatial coordinates on the grid;

M = the mass discharged during each time step;

t = elapsed time;

D_x, D_y, D_z = the dispersion coefficents in the three grid directions; and

X_d, Y_d, Z_d = the displacement of the centre of the cloud.

and erf (the error function) = $\frac{2}{\sqrt{\pi}} \int_0^x e^{-\sigma^2} d\sigma$

The error function, a standard mathematical expression, is numerically approximated to simplify calculation.

2.2.1 Assumptions

1. It is assumed that the field in which the model is applied is uniform. Currents flow uniformly through the field at a rate and direction used in

the calculations. Settling and rising of materials likewise occurs at a constant rate.

2. The nature of the material being modelled is uniform. Particles, for example, are of uniform size and settle at a constant rate.

3. The material under study is conserved throughout the dispersion process. The material has not been chemically or mechanically altered during dispersion.

4. The material being dispersed is passive in the marine environment. It does not affect the water itself so as to alter the dispersion process.

Advantages

The model has several advantages. It is arithmetically simple; the amount of computing time required allows for a large number of experimental runs to test the effect of a wide range of dispersive conditions; it permits the manipulation of individual parameters to test the effect of changes in specific variables; thus, the effect of vertical velocity, diffusion coefficient, discharge duration and many other factors can be calculated and evaluated. Sensitivity runs can be (and were) done to provide ranges of concentrations under extremes of current, settling and rising velocity, and stratification.

2.2.2 Calculations

Model calculations were made using the production waste discharge scenarios for each of the three regions (see Chapter 7, Section 3). For each area advective displacement was expressed as a function of mean current velocity and direction at a stated depth for the water column, tidal velocities on the semi-major and semi-minor axis, and tidal period and tidal axis orientation to the mean current flow. Grid size was held at 1000 metres for site-specific runs, although smaller grid sizes were used in studying the effect on the model of varying selected theoretical parameters. The diffusion coefficient selected was one $m^2 s^{-1}$ in the horizontal direction and 10^{-3} $m^2 s^{-1}$in the vertical. This would represent a "worst-case" situation in which settling would be minimal due to high stratification, thus producing a wider range of particle/dense substance dispersion. Duration of discharge was varied according to the type and practice of discharge under study.

The time increment for calculating successive concentrations was carefully considered. It was found that different model time increments did not necessarily produce identical grid concentrations from equal initial discharge concentrations. This was assumed to be the result of two separate model idiosyncrasies. If time t_2 is exactly twice time increment t_1, and discharge masses are adjusted to produce identical initial concentrations, the first calculation of concentration for run t_1 will produce a higher value than the first of t_2, since t_1 has permitted less time for dispersion to occur. During the second calculation of t_1, logically one would expect the same concentration as t_2 ($t_1 + t_1 = t_2$), but this second calculation has taken into account a new, fresh cloud of the original concentration which was introduced at the beginning of the second period. As a result, the grid concentrations produced by increment t_1 and t_2 will be similar, but not the same.

The second effect of time increment on concentration involves sampling of the tidal ellipse. The data for tidal period, semi-major and semi-minor axis velocities and axis orientation produce a mathematical tidal ellipse which is sampled in the calculation to produce a tidal velocity vector to be used in calculating the advective displacement of the cloud. Most tidal ellipses are pronounced, so sampling for velocity at one hour intervals from a reference point will obviously produce a different velocity than sampling at one half-hour intervals. If such differing values are used in successive modelling calculations, slight differences in cloud movement will occur. The result will be slightly different grid concentrations from differing calculation increments.

In either case the effect of time increment on concentration will decrease as dt approaches 0. The disadvantage to extremely small dt values in practice, however, is that the number of calculations required for each run increases in inverse proportion to increment size. Eventually, a time increment of 30 minutes was selected for use in modelling the regional scenarios. The thirty-minute period represented a levelling point for the effect of dt on concentration. The difference between calculated values for dt = 30 minutes and dt = 15 minutes was determined to be acceptable in view of the precision of other input parameters.

2.2.3 Input Data

Data for water currents and settling and rising velocities used in the dispersion model are given in Table 8-11. The measurements of water currents were made in each offshore zone, but the number of measurements is small. Consequently, the values used in the dispersion model may not be representative of specific areas.

2.2.4 Sensitivity Analysis

The factors which strongly influence dispersion are current velocity, dispersion coefficient and settling velocity. Model runs were made to determine the sensitivity of the model for each of these quantities. The results are shown graphically in Figures 8-1, 8-2 and 8-3 for current velocity, dispersion coefficient and settling velocity, respectively.

The results show that the calculated dilution factors can vary by as much as 10^3, 10^2 and 10^4 for the ranges considered to be possible for current speed, dispersion coefficient and settling velocity, respectively.

2.2.5 Output Data

Each model run yields a dilution factor (based on an initial concentration of unity) at each of the grid points. The dilution factors were used to determine the accumulation of a particular chemical component at each grid point so as to indicate a zone of influence of the discharge (see 3.0 below). The graphical presentation of the output data is shown in Figures 8-4 to 8-17.

The steps involved in constructing the figures is illustrated for chromium in drilling waste effluent being discharged into the surface waters on the Scotian Shelf. The total discharge of waste drilling fluid from a single well on the Scotian Shelf is estimated to be 3,100 m^3 (see Table 7-5). The concentration of Cr in this waste is estimated at 190 mg/L (see Table 7-5). The total input of chromium into the receiving waters, therefore, is 5.89×10^8 mg. It is assumed that 80% of the waste drilling fluid settles to the bottom within 200 m of the discharge point. There is ample field evidence to support this assumption. Neff (1982), for example, has summarized results from field investigations of the dispersion and dilution of drilling mud slurries in the water column and the deposition of the drilling muds in bottom

TABLE 8-11

PHYSICAL DATA USED IN THE DISPERSION MODEL

	SCOTIAN SHELF[a]	GRAND BANKS[b]	BEAUFORT SEA[c]
Typical Residual Current Velocity	0.09 m s^{-1}	0.024 m s^{-1}[d]	0.04 m s^{-1}
Maximum Mean Residual Current Velocity	0.15 m s^{-1}	1.0 m s^{-1}[e]	0.082 m s^{-1}
Tidal Currents			
Semi Major Axis	0.30 m s^{-1}	0.26 m s^{-1}	0.02 m s^{-1}
Semi Minor Axis	0.04 m s^{-1}	0.18 m s^{-1}	0.003 m s^{-1}
Angle to Mean Current	40°	90°	90°
Period	12.42 hours	12.42 hours	12.42 hours
Settling Velocity[f]	0.3×10^{-3} m s^{-1}	0.3×10^{-3} m s^{-1}	0.3×10^{-3} m s^{-1}
Rise Velocity[g]			
0.5 mm Droplet	$- 1.548 \times 10^{-02}$ m s^{-1}	$- 1.548 \times 10^{-02}$ m s^{-1}	$- 1.548 \times 10^{-02}$ m s^{-1}
0.05 mm Droplet	$- 0.155 \times 10^{-02}$ m s^{-1}	$- 0.155 \times 10^{-02}$ m s^{-1}	$- 0.155 \times 10^{02}$ m s^{-1}

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[a] MacLaren Plansearch Ltd. 1982
[b] Petrie 1982
[c] Huggett et al. 1977
[d] mean of the observed current
[e] maximum residual current

[f] settling velocities are those given for 20 μm quartz spheres (A.S.C.E. 1975). Approximately 80% of all particles expelled in a mud dump are between 10 and 50 μm in size; by weight, 60% of the material comprises particles between 10 and 20 μm grain size (Ayers et al. 1980 a).

[g] in the laboratory, droplet sizes from 0.001 to 0.030 mm are produced in simple crude oil/seawater mixtures (Gordon et al. 1973). Samples of tanker ballast water have yielded droplet sizes from 0.015 to 0.100 mm (Witman and Gollan, 1973). A droplet size of 0.050 mm was selected as a midpoint in the range for the calculations in this study. Calculations were, however, also made for droplets of 0.5 mm as an indication of the dispersion of larger particles. Droplets larger than 0.5 mm rise to the surface in several minutes (rise velocities of droplets are based on Wicks, 1977). The particle size of oil introduced into sea water either by discharge or washing of sediments would probably be in the 20 μm range (pers. comm. McKay).

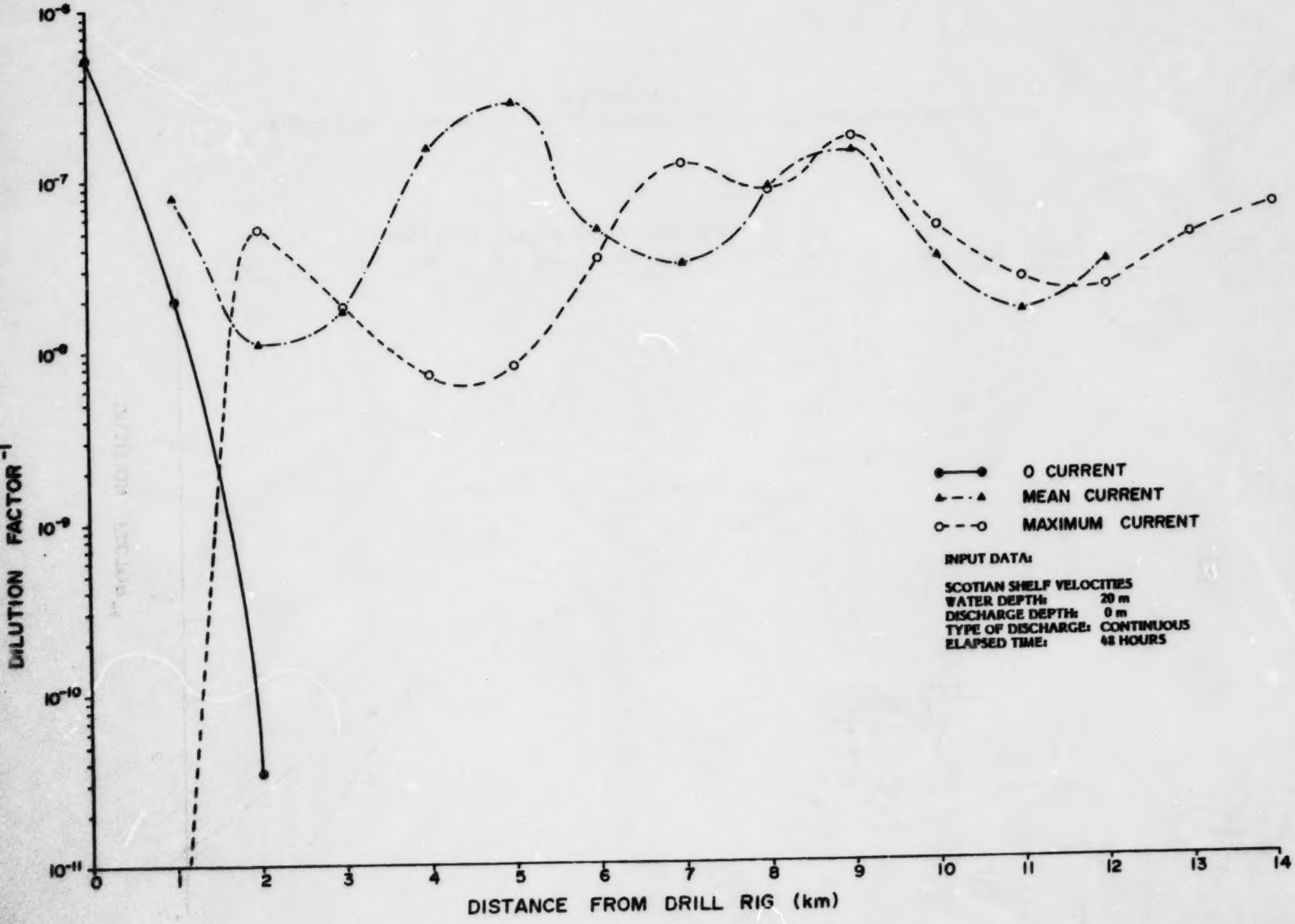

Figure 8-1. Sensitivity of dilution factors calculated by dispersion model to current velocity for the Scotian Shelf areas.

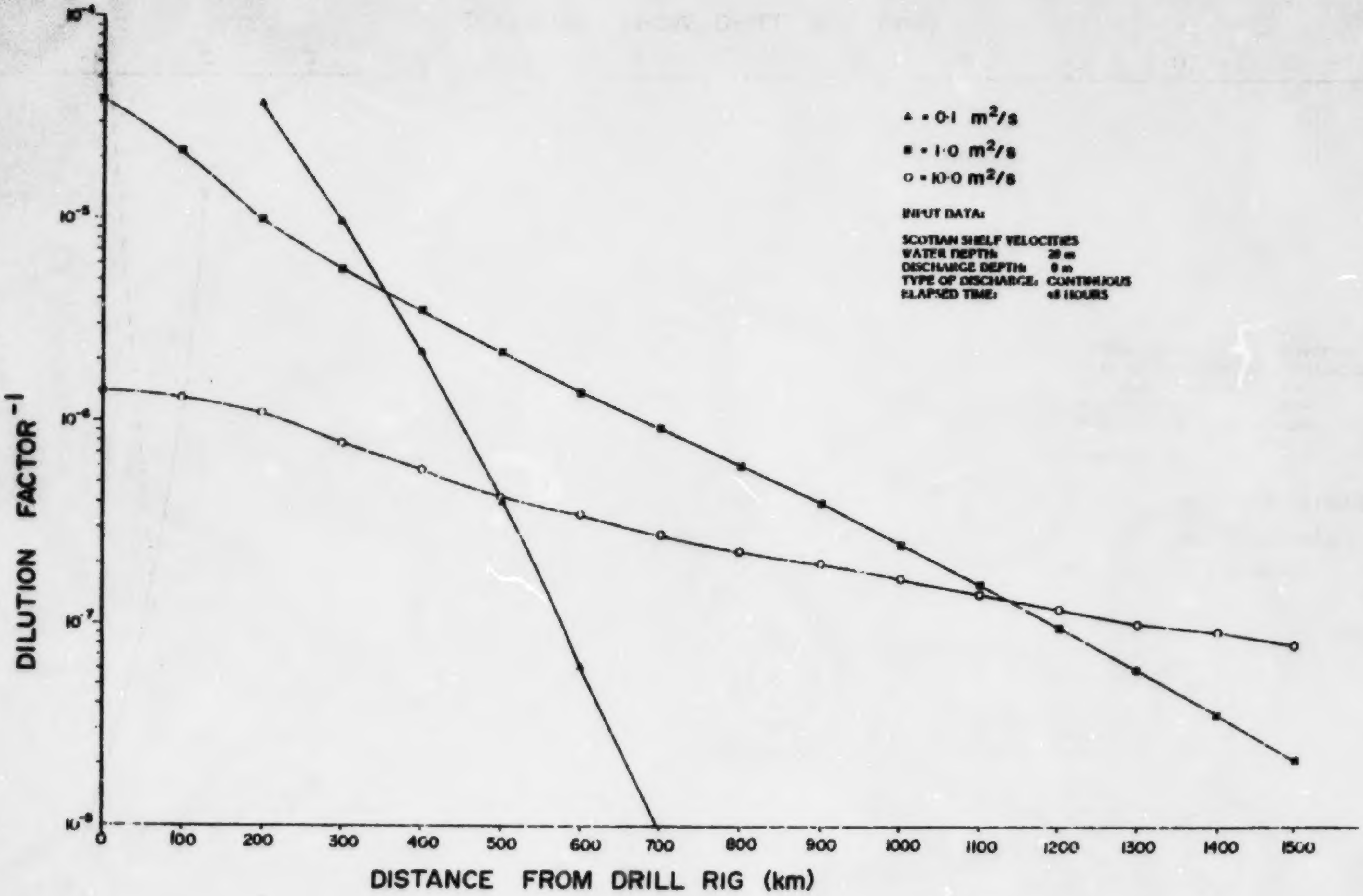

Figure 8-2. Sensitivity of dilution factors calculated by the dispersion model to dispersion coefficient.

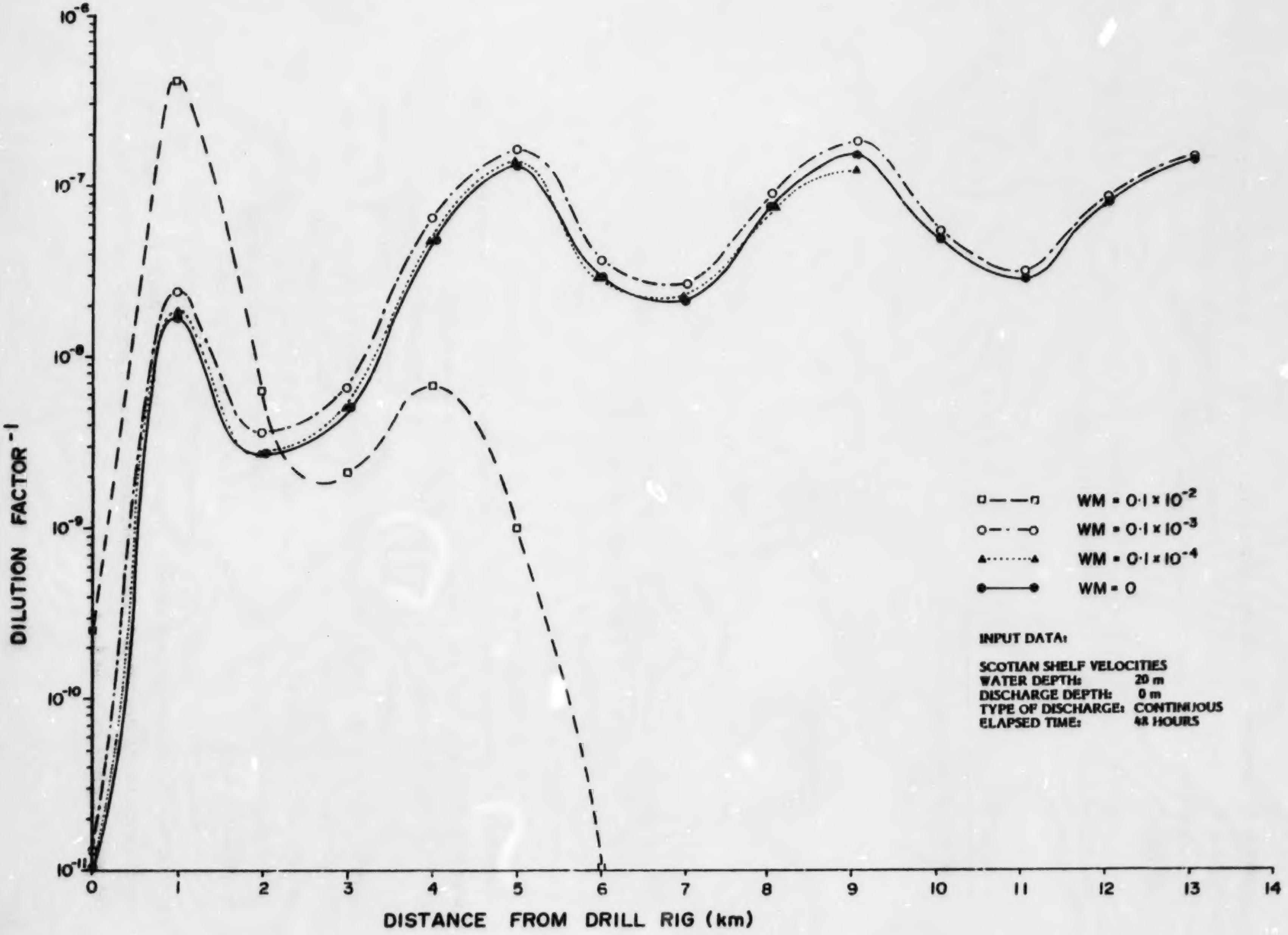

Figure 8-3. Sensitivity of the dilution factors calculated by the dispersion model to particle settling velocity.

sediments. All of the studies showed that most of the metal enrichment in the sediment occurred within 100 metres of the discharge point; background concentrations were usually reached within 1,000 metres down-current from the discharge.

Assuming that no direction is preferred for deposition, the average annual accumulation of Cr within 200 m of the platform would be:

$$\frac{\text{total input of Cr from 1 well}}{\text{area of circle with } r = 200 \text{ m}} \quad \times \quad \begin{array}{c}\text{Number of wells}\\ \text{drilled per year}\end{array} \quad \times \quad \begin{array}{c}\text{fraction of}\\ \text{discharge}\\ \text{settling out}\\ \text{within 200 m}\\ \text{of rig}\end{array}$$

$$= \quad \frac{5.89 \times 10^{8} \text{ mg}}{1.26 \times 10^{5} \text{ m}^{2}} \quad \times \quad \frac{40 \text{ wells}}{3 \text{ years}} \quad \times \quad 0.8$$

$$= \quad \text{approx. } 50{,}000 \text{ mg m}^{-2} \text{ a}^{-1}$$

The factor of 40/3 comes from the development scenario which calls for 40 wells to be drilled from a single offshore platform during a period of three years.

The 20% of the total discharge that is dispersed beyond 200 m of the discharge point is distributed according to the dilutions calculated from the model run. The area of maximum accumulation (smallest dilution factor) is obtained by inspection of the computer printout. **The dilution factors are steady-state values which correspond to continuous discharge conditions.** They are arranged asymmetrically around the discharge location. The distribution depends on the input values for current speed, tidal components, water depth and other factors. The quantity of Cr discharged at each grid point is calculated. Accumulation rates are calculated assuming that, on a yearly average, the discharge will be evenly distributed around the platform; they are plotted as a function of distance from the discharge source. The points are plotted at distances corresponding to the mid-points of annulae 0.5-1.5, 1.5-2.5, 2.5-3.5 km etc. around the discharge point.

The accumulation of Cr in sediments of the Scotian Shelf from natural sedimentation is also placed on the dispersion graph as a basis for judging the significance of the discharge from the platform. Natural accumulation rates for each element are given in Table 8-12.

TABLE 8-12

NATURAL ACCUMULATION RATES* OF HEAVY METALS IN SEDIMENTS ON THE SCOTIAN SHELF, GRAND BANKS AND BEAUFORT SEA SHELF

1. SCOTIAN SHELF

ELEMENT	TYPICAL CONCENTRATION IN SEDIMENT (see Table 8-2) $\mu g\ g^{-1}$	ACCUMULATION RATE $mg\ m^{-2}\ a^{-1}$
Cr	130	650
Ni	80	400
Cu	10	50
Cd	0.04	0.2
Pb	8	40
Hg	0.10	0.5
Zn	60	300
hydrocarbons	50	250

2. GRAND BANKS

ELEMENT	TYPICAL CONCENTRATION IN SEDIMENT (see Table 8-5) $\mu g\ g^{-1}$	ACCUMULATION RATE $mg\ m^{-2}\ a^{-1}$
Cr	87	435
Ni	36	180
Cu	25	125
Cd	0.26	1.3
Pb	21	105
Hg	0.10	0.5
Zn	84	420
hydrocarbons	50	250

3. BEAUFORT SEA SHELF

ELEMENT	TYPICAL CONCENTRATION IN SEDIMENT (see Table 8-8)** $\mu g\ g^{-1}$	ACCUMULATION RATE $mg\ m^{-2}\ a^{-1}$
Cr	55	275
Ni	46	230
Cu	28	140
Cd	0.28	1.4
Pb	9	45
Hg	0.08	0.4
Zn	118	590
hydrocarbons	100	500

* Accumulation rates based on the following data:

1. average sedimentation rate = 0.45 cm a^{-1}
2. sediment porosity = 60%
3. sediment specific gravity = 2.7

** unweighted average (all results)

The shape of the discharge curves are the same for each component; only the relation between anthropogenic and natural inputs is specific to each chemical component.

3.0 Zone of Influence

The zone of influence resulting from the discharge of a substance at a point source can be regarded as the zone within which an effect attributable to the discharge can be distinguished with confidence from the natural background condition. The accurate delineation of a zone of influence resulting from a multi-component, heterogeneous discharge (such as waste drilling fluid and certain other production wastes) into the marine environment is a very complicated undertaking because many inter-dependent and dynamic processes act simultaneously. For this reason, it was necessary to apply a series of simplifying assumptions (see Section 2.2.1) to the model used in this report to simulate the dispersion of production wastes. These assumptions and the general lack of detailed input data for oceanographic conditions at each of the proposed offshore hydrocarbon production areas severely limits the capacity of the model for making quantitative predictions on a small scale (approx. ± tens to ± hundreds of metres). It is not expected, therefore, that the model would be able to provide realistic estimates for the concentration of a given chemical substance at a particular position in space and time. An approximate representation of the average nature and extent of a zone of influence, however, is probably a reasonable expectation of the model on a scale of about one kilometre. This is unproven, however, because the validity of the model has not been tested with real field data, for none exist.

Several factors affect the delineation of a zone of influence. These include:

(1) Choice of effect used to measure the zone

The areal extent of the zone of influence around a point source will depend on the choice of effect used to measure it. Specifically, a zone of influence based on physical disturbance will differ from that based on the presence or absence of a specific chemical compound; both will differ from that based on some biological effect. In this report, we restrict the term "zone of influence" to mean that zone within which the presence of an added substance can be detected with confidence against the natural background condition; that is, the concentration or accumulation rate of a substance can be displayed graphically as a function of distance away from the point source. The zone is thus a physical/chemical one; it is stressed that no statement is being made in this report regarding a biological zone of influence or any cause and effect relationships in conjunction with the results of the model runs because many factors not considered here must be taken into account. These include bioavailability of various discharged substances; susceptibility of species living in each offshore zone to those substances; expected exposure times; seabed disturbances and alterations resulting from short-term diagenetic processes.

2) Sensitivity of the detection technique

The output of the dispersion model yields a field of steady state dilution factors around a point source which discharges waste continuously. The presence of vanishingly small quantities of discharge constituents can be resolved arithmetically by the model. This leads, in theory, to an infinite zone of influence. The practical limit of the zone of influence, however, will be much smaller; it will depend on the accuracy and sensitivity of the method of detection for the substance used as a tracer of the discharge. This in turn will depend on the relative magnitude of the amount of a tracer substance discharged to the amount present as background and its natural variability. Barium and chromium in drilling mud waste illustrates the point: Trocine et al. (1981; cited in Neff 1982) reported that surficial sediments 1.9 km downstream of the discharge from an exploratory rig in the Gulf of Mexico contained a three-fold above background barium concentration; yet, chromium concentrations did not deviate significantly from normal at any station. These observations result from barium being much more enriched in the particulate discharge relative to the background barium concentrations in the surrounding surficial sediments than was the case for chromium.

3) Fractionation of the discharge

The zone of influence may vary among constituent components of an heterogeneous discharge as a result of physical fractionation. This is

> generally true of waste drilling fluids: The zone of influence of those chemical substances which are preferentially enriched in the heavy fraction of the drilling fluid will be smaller than the zone of influence of those chemical substances more plentiful in the lighter fractions of the drilling fluid. This occurs because the denser fractions tend to be deposited nearest the discharge source whereas the fractions of lesser density sink more slowly thereby allowing them to travel farther from the discharge source before encountering the seabed.

It is important to recognize the limitations of the model results presented below by considering several factors that influence them. First, the dispersion and ultimate deposition of only 20% of the discharged solids are actually modelled because an initial condition imposed on the model was that 80% of the discharged solids would settle to the seabed within 200 metres of the discharge pipe. The accumulation rates shown, therefore, could be higher or lower depending on whether the amount of material remaining in the water column after the initial slug of solids settles to the bottom is higher or lower than the assumed 20%. Second, sedimentation rates were taken as 4.5 mm a^{-1} for all three offshore areas. If the true sedimentation rates are lower than this, then the difference between the background accumulation rates and discharge-related accumulation rates for any given substance will decrease. Third, the model does not take into account any redistribution of sedimentary material after deposition. Mechanisms for the redistribution of the material on the seabed are, in general, well known, but the extent to which redistribution will occur at specific locations is unknown. Ice scour and infrequent but vigorous storm events are processes relevant to the bottom resuspension and dispersal of sediments in the Beaufort Sea shoreward of the 20 m isobath. The very mobile bed forms on the Scotian Shelf would be an important mechanism for mixing and transporting discharged waste materials. Bottom scouring currents could play a large role in the redistribution of discharges in all three zones.

3.1 Sediments

3.1.1 Heavy Metals

The output data from the dispersion model were used to calculate accumulation rates of Cr, Cu, Cd, Pb, Hg and Zn in the sediments that can be compared to known natural rates of accumulation for the same metals. The results are shown in Figures 8-4 to 8-9 for the Scotian Shelf and Figures 8-10 to 8-15 for the Beaufort Sea. There are no data given for the Grand Banks because dilutions were very large (accumulation rates less than 0.1% of natural background) and did not reach equilibrium within 10 km of the discharge point.

The figures referred to above which depict the rate of accumulation of metals as a function of distance from the discharge are better understood within the context of the physical events that occur after discharge. Drilling mud is a highly heterogeneous slurry of a variety of solid particles in water which contains various dissolved components. The different solid and dissolved components have different densities. Consequently, when drilling mud is discharged to the sea, it undergoes rapid fractionation. Most of the material (at least 80%) falls rapidly to the bottom under its own momentum and settles within 200 m of the discharge source. Two plumes are usually formed. The first occurs near the bottom and is associated directly with the slug of dense (about 2.0 g cm^{-3}) material. The second plume occurs at the surface; it comprises the low-density fine clay-sized particles; this upper plume is formed through turbulent mixing of the lower plume with sea water. The upper plume contains about 20% of the total mass discharged; it persists much longer than the lower plume. The plume disperses downcurrent and the particles settle out at distances from the origin that are determined by strength of the water currents and depth of the water.

The figures combine the effects of the two plumes on the accumulation of metals in the bottom sediments; the contributions from each plume are shown separately on the figures (this has been done for the sake of simplicity; in fact, the accumulation of metals in the sediments resulting from each plume would blend into a continuum). The solid bar along the ordinate axis represents the accumulation of 80% of the discharged material within 200 m of the discharge point; this is the amount associated with the slug of dense material (the choice of 80% was approximate; see Section 2.2.5). The curve gives the accumulation in the sediments of the remaining 20% of the discharged material (the upper plume) downcurrent from the source as determined by the dispersion model calculations using the input data given in Table 8-11. The shape of the curve depends on the current field. The multimodal distribution observed for the Scotian Shelf results from the strong tidal influence. By comparison, the curves for the Beaufort Sea show a rapid, continual decrease in concentration with distance from the discharge. This results from the

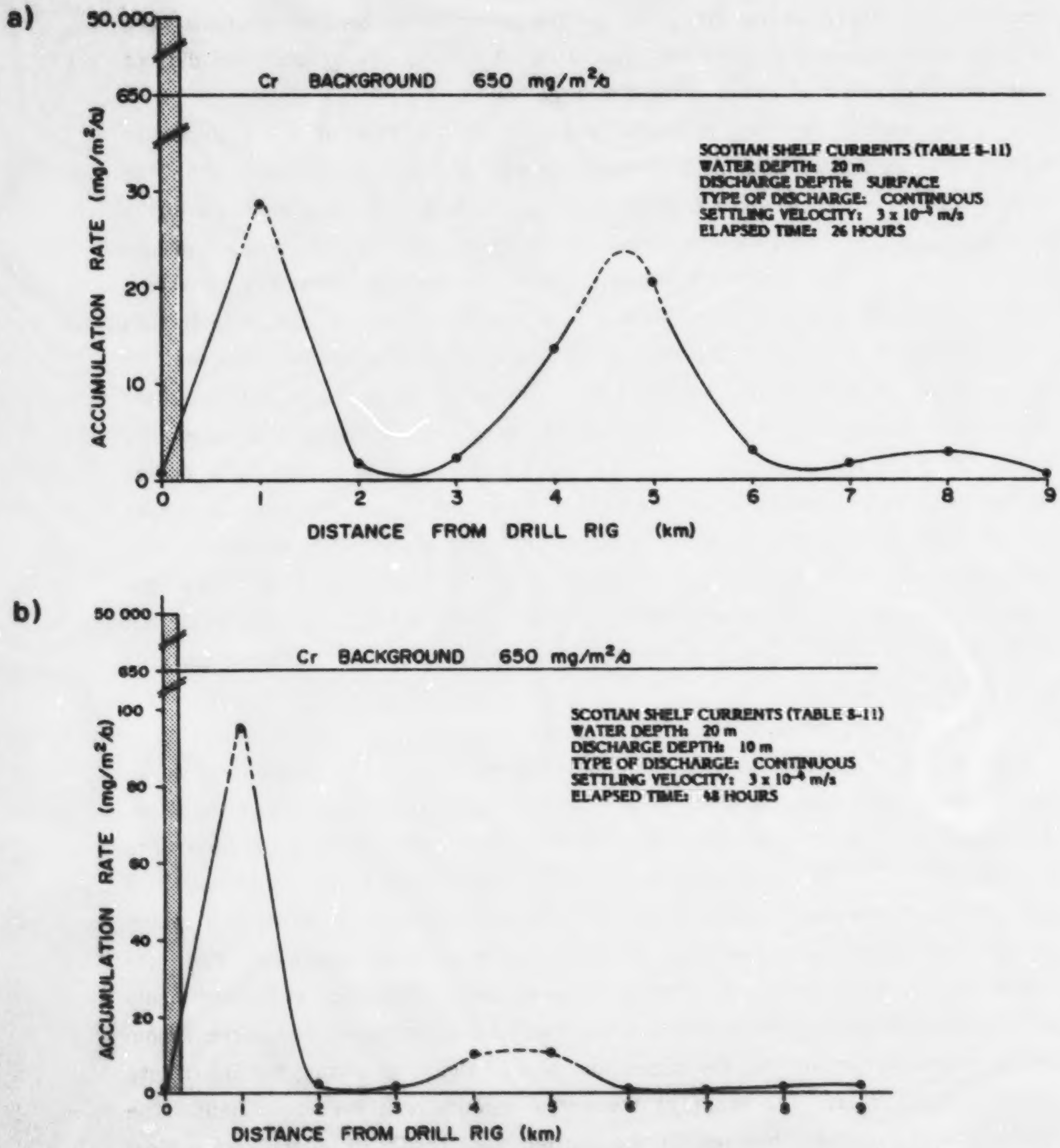

Figure 8-4. Accumulation of chromium in sediment of the Scotian Shelf down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

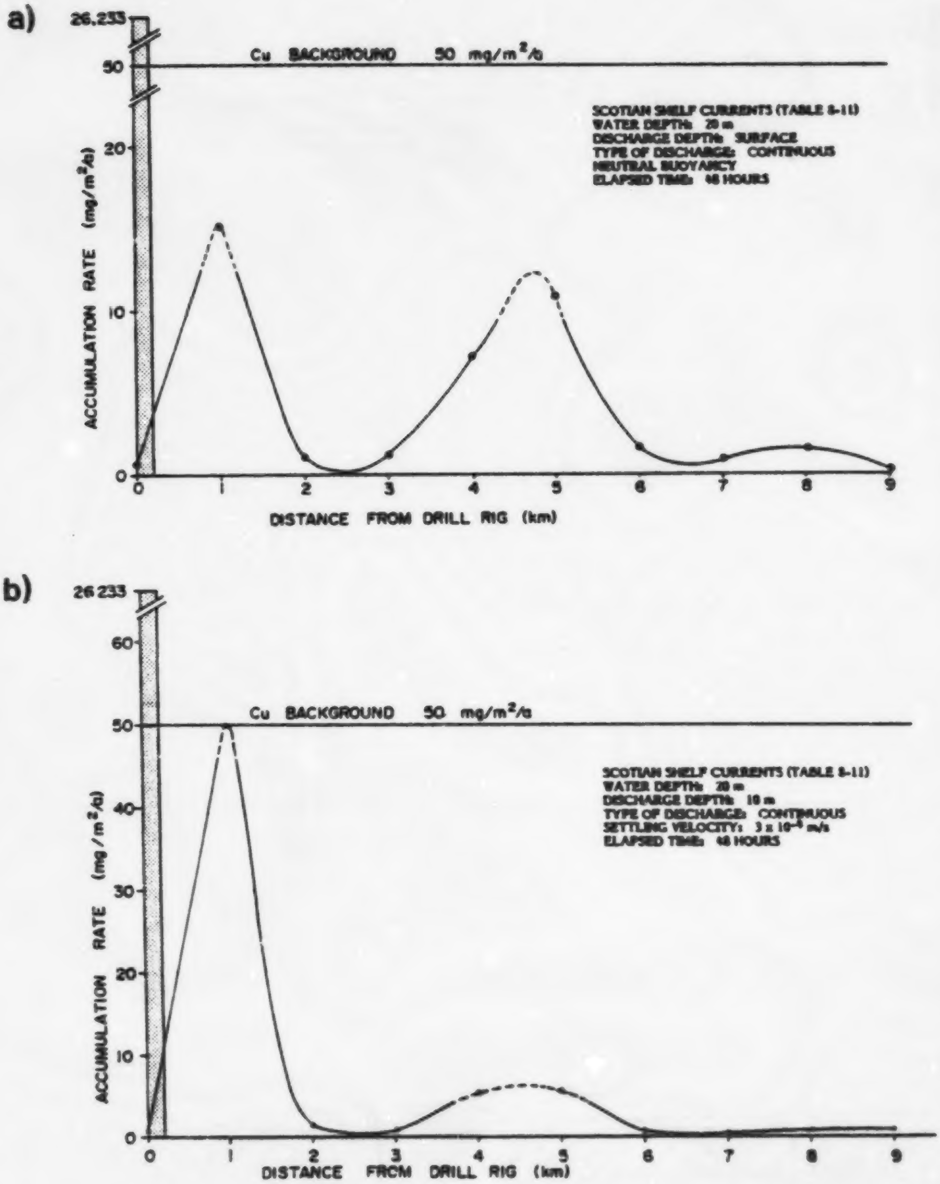

Figure 8-5. Accumulation of copper in sediment of the Scotian Shelf down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

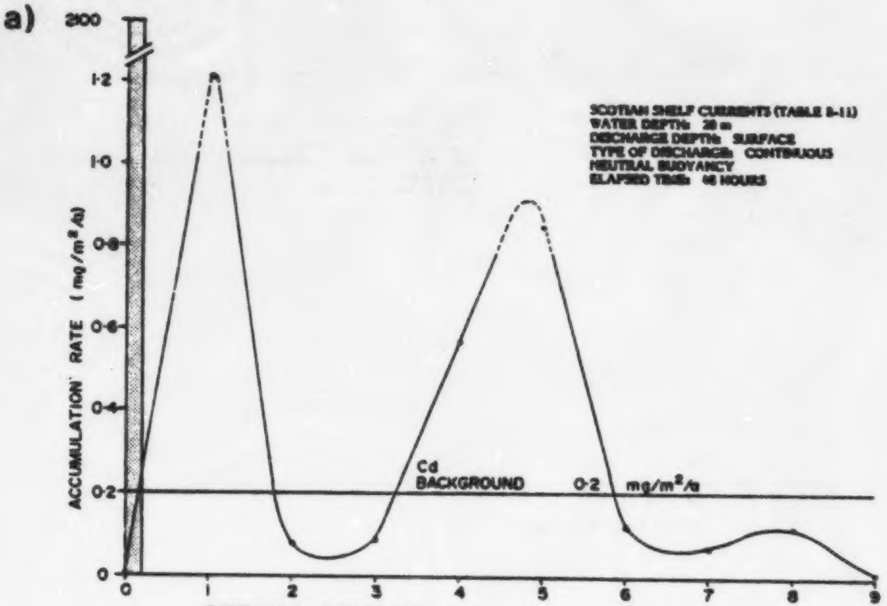

Figure 8-6. Accumulation of cadmium in sediment of the Scotian Shelf down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

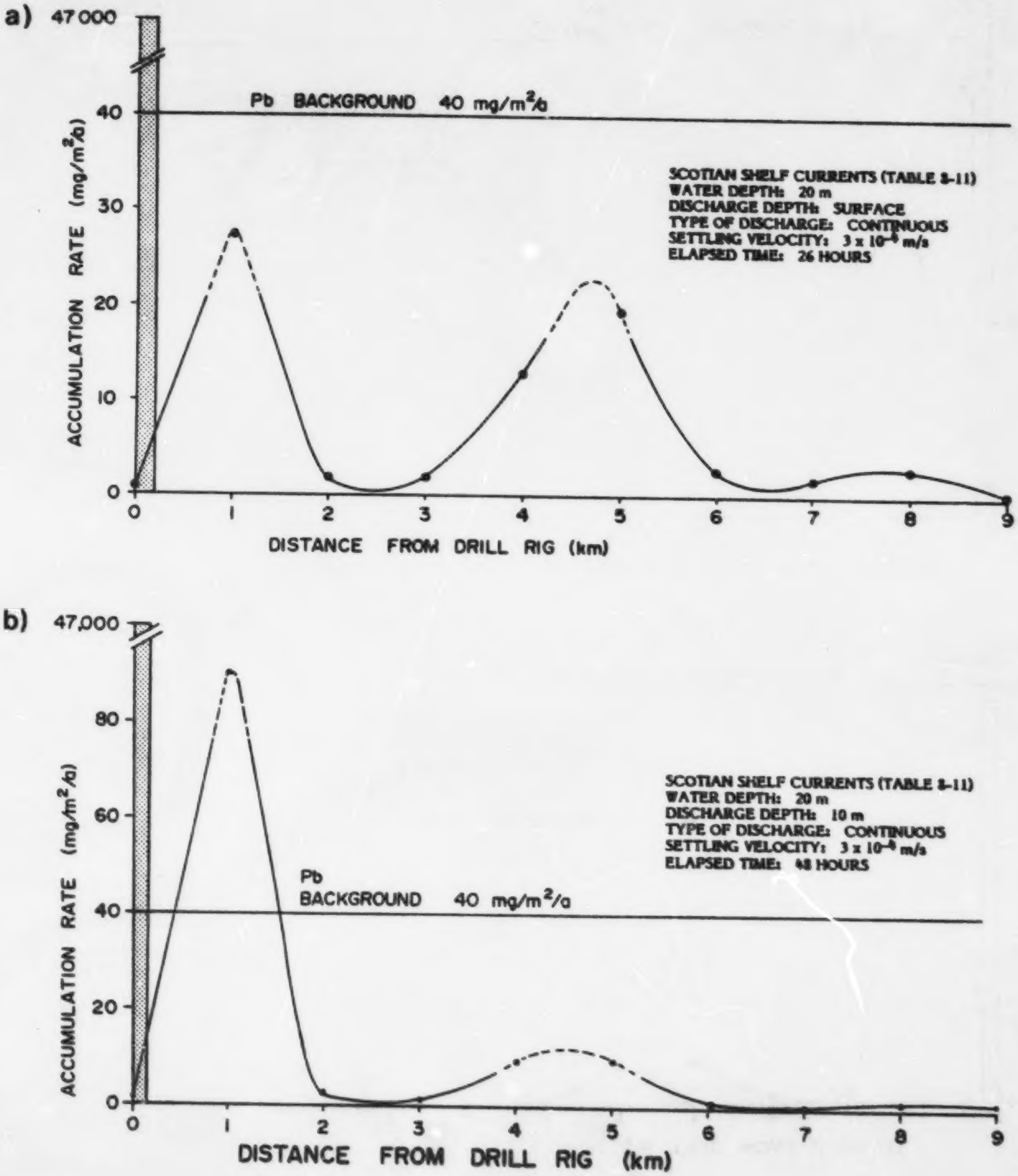

Figure 8-7. Accumulation of lead in sediment of the Scotian Shelf downcurrent from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

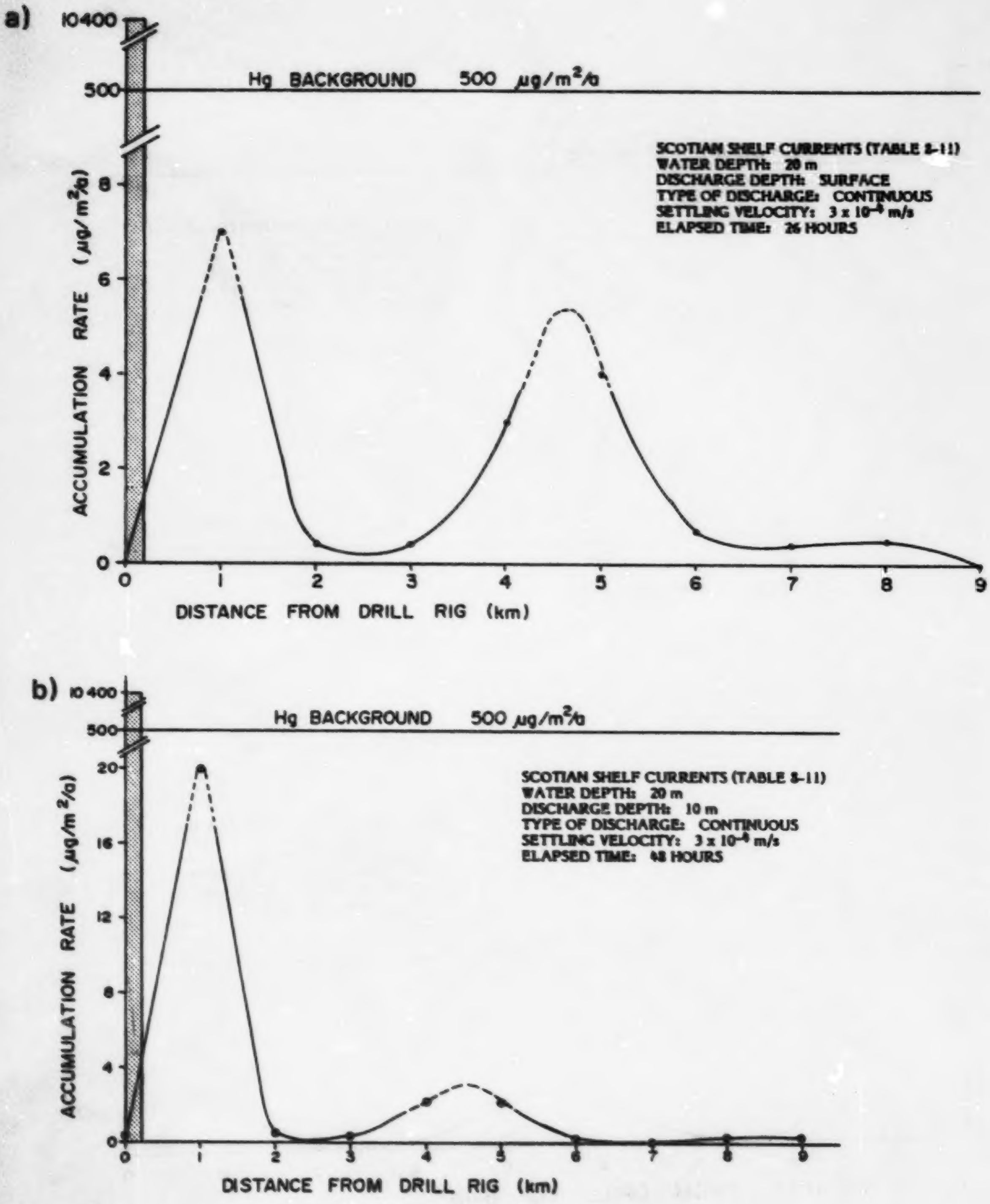

Figure 8-8. Accumulation of mercury in sediment of the Scotian Shelf down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

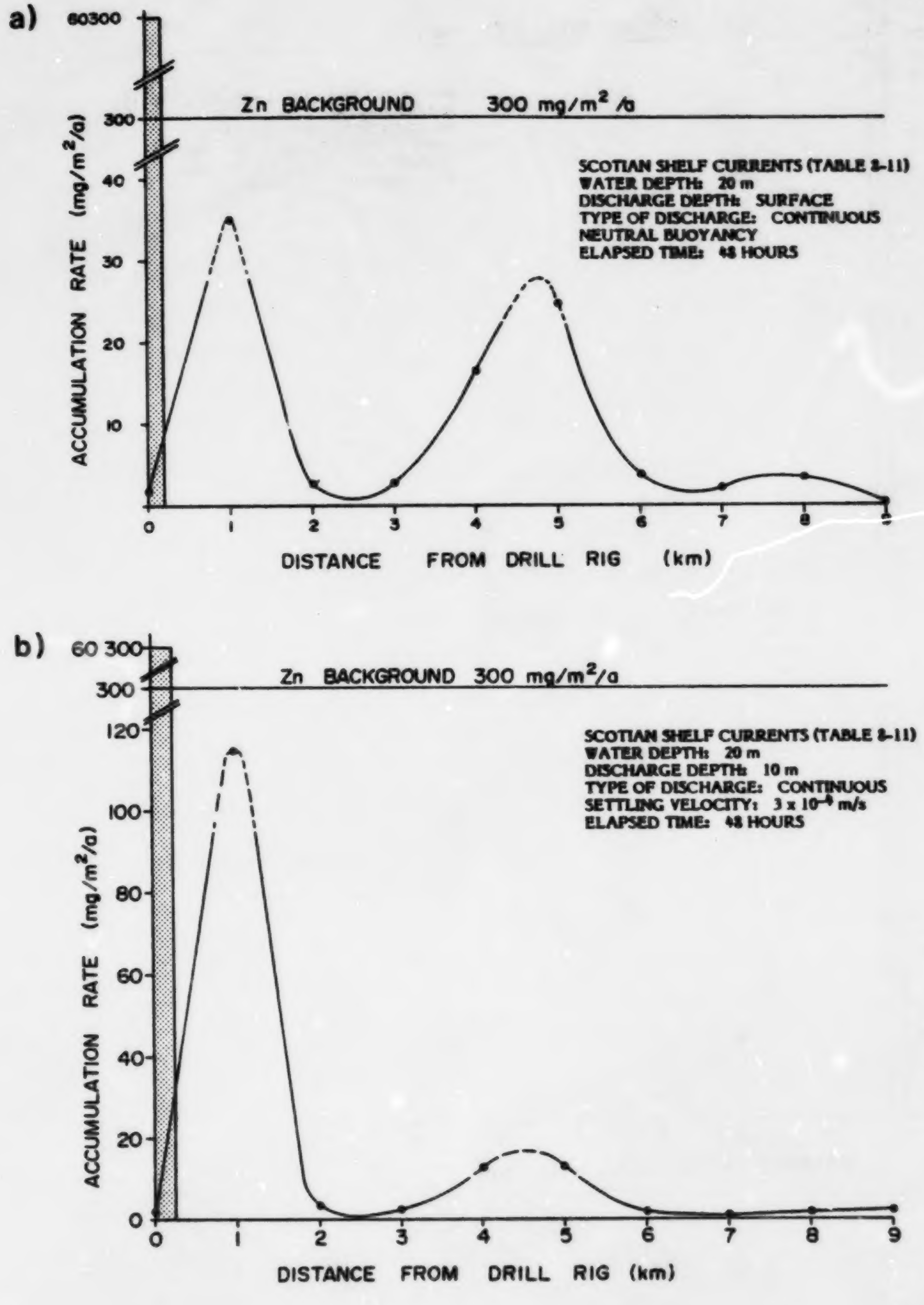

Figure 8-9. Accumulation of zinc in sediment of the Scotian Shelf down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

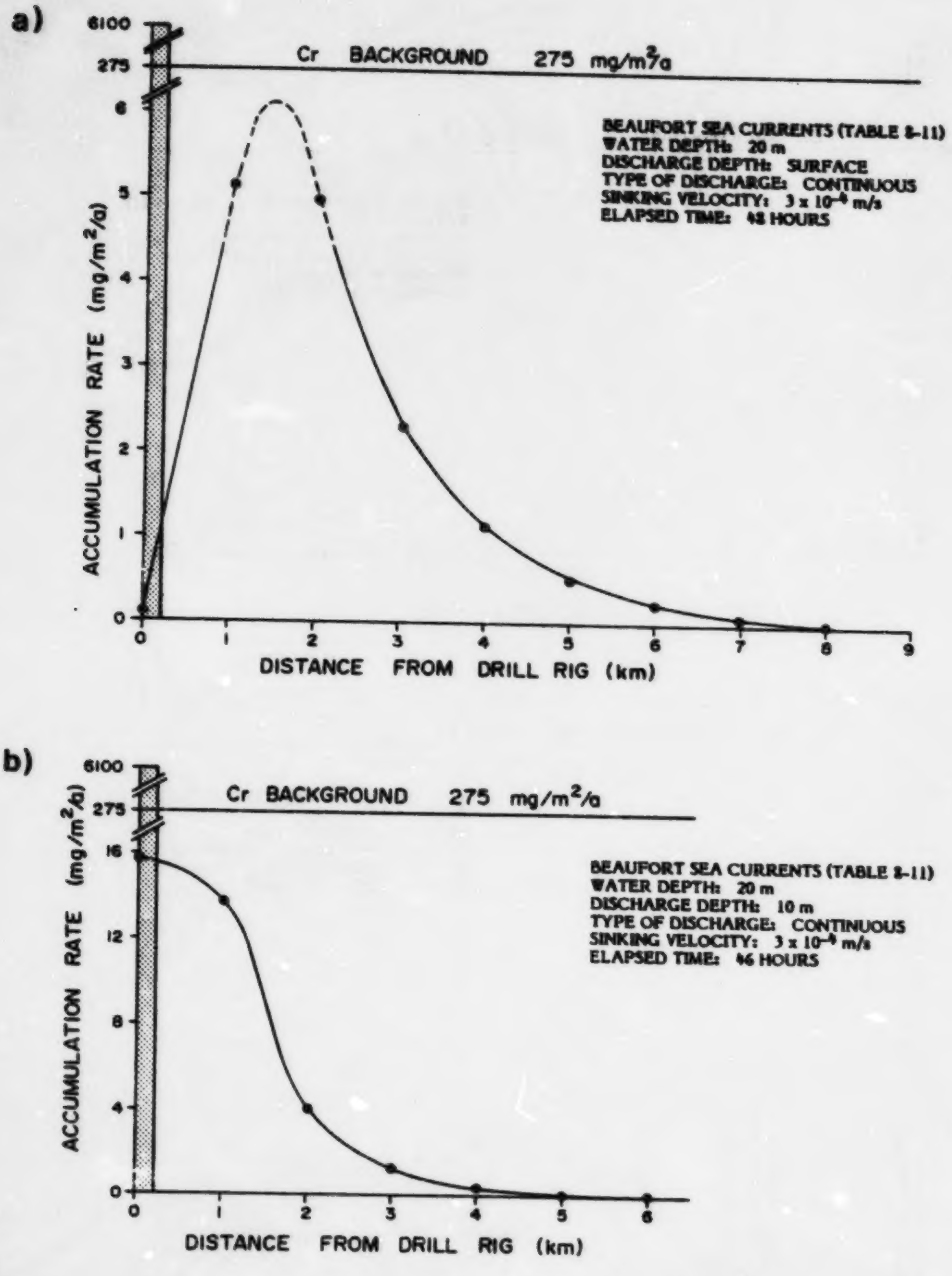

Figure 8-10. Accumulation of chromium in sediment of the Beaufort Sea down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

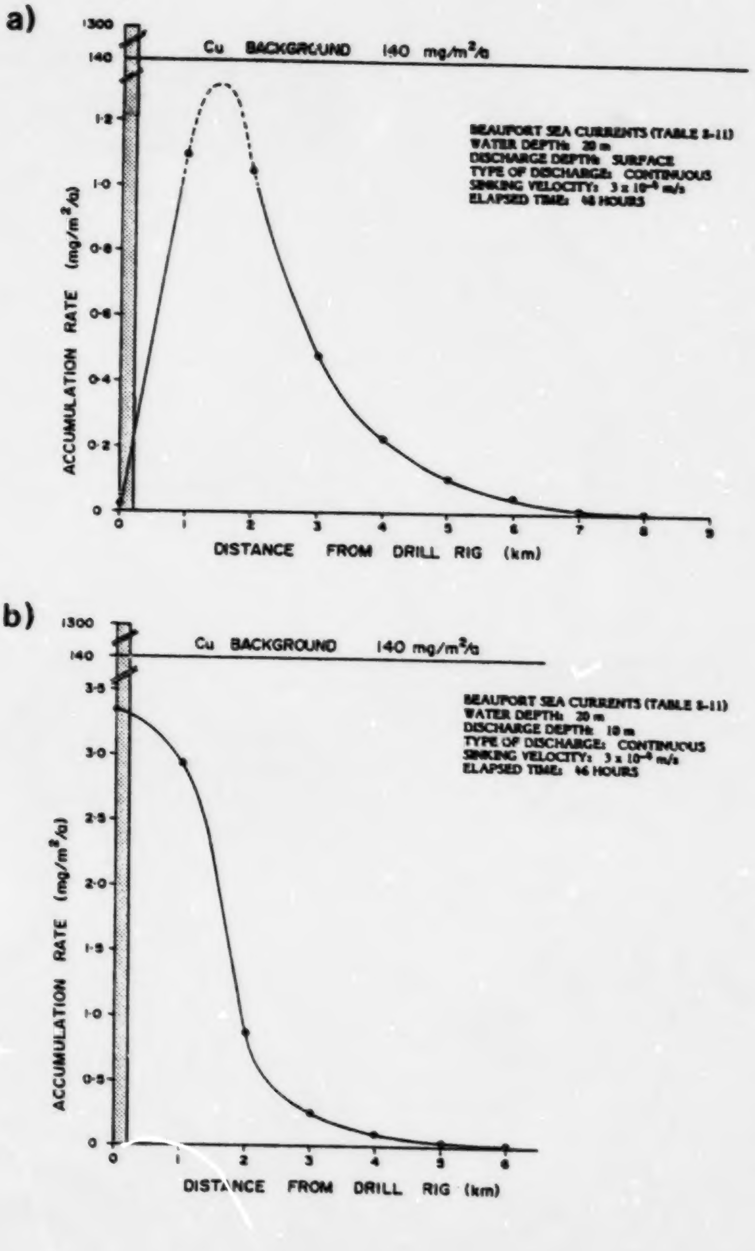

Figure 8-11. Accumulation of copper in sediment of the Beaufort Sea down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

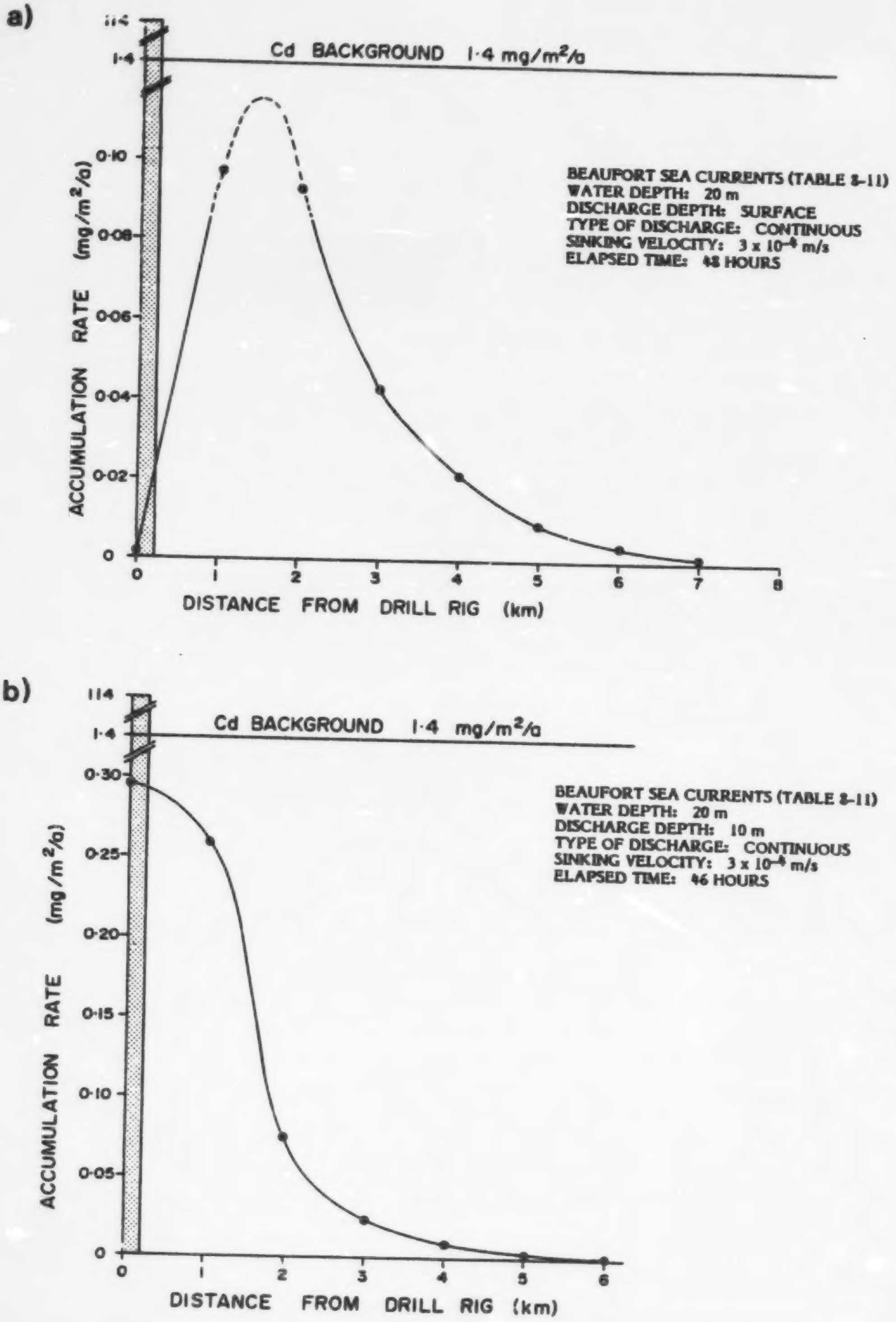

Figure 8-12. Accumulation of cadmium in sediment of the Beaufort Sea down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

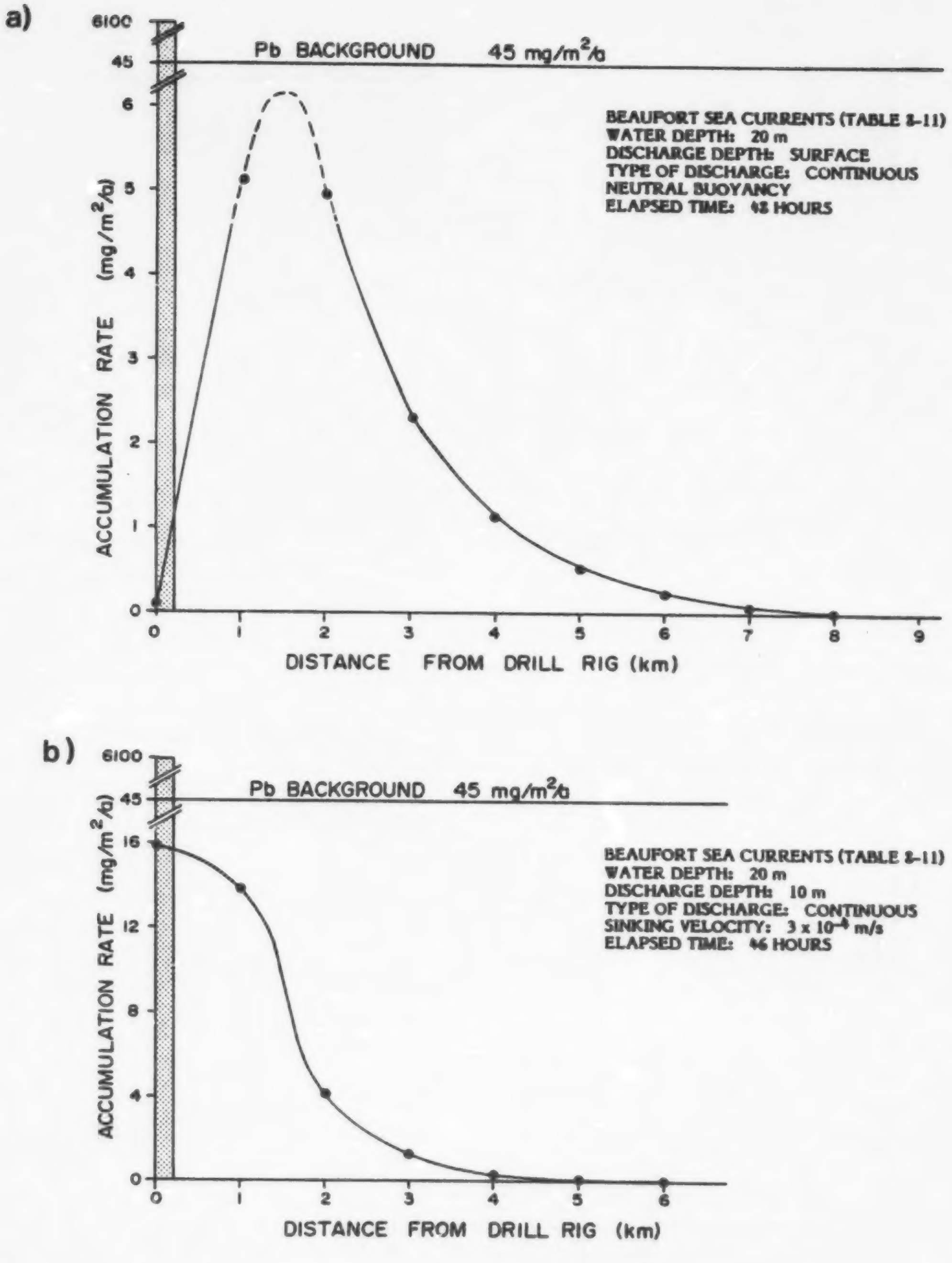

Figure 8-13. Accumulation of lead in sediment of the Beaufort Sea down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

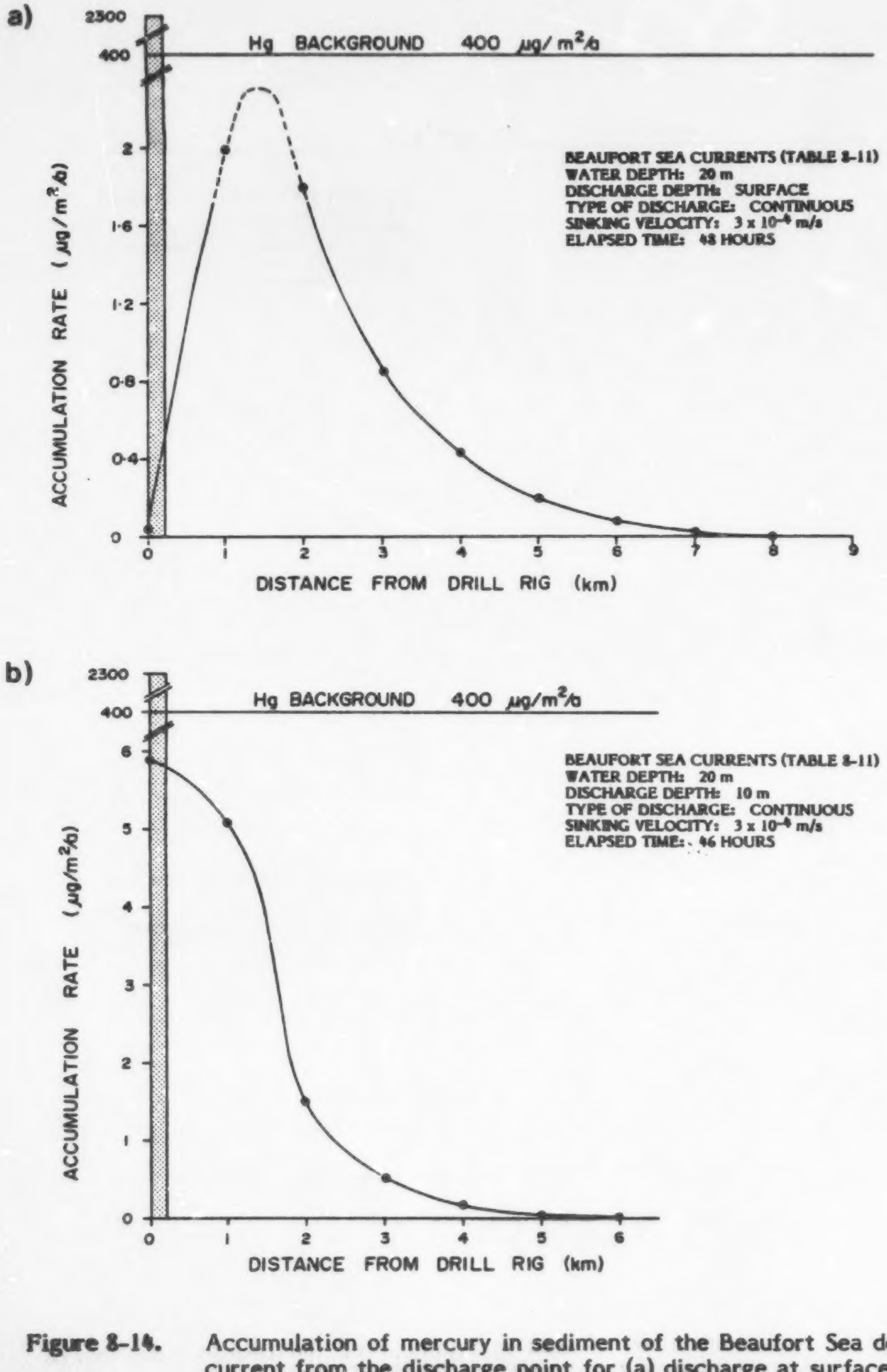

Figure 8-14. Accumulation of mercury in sediment of the Beaufort Sea downcurrent from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

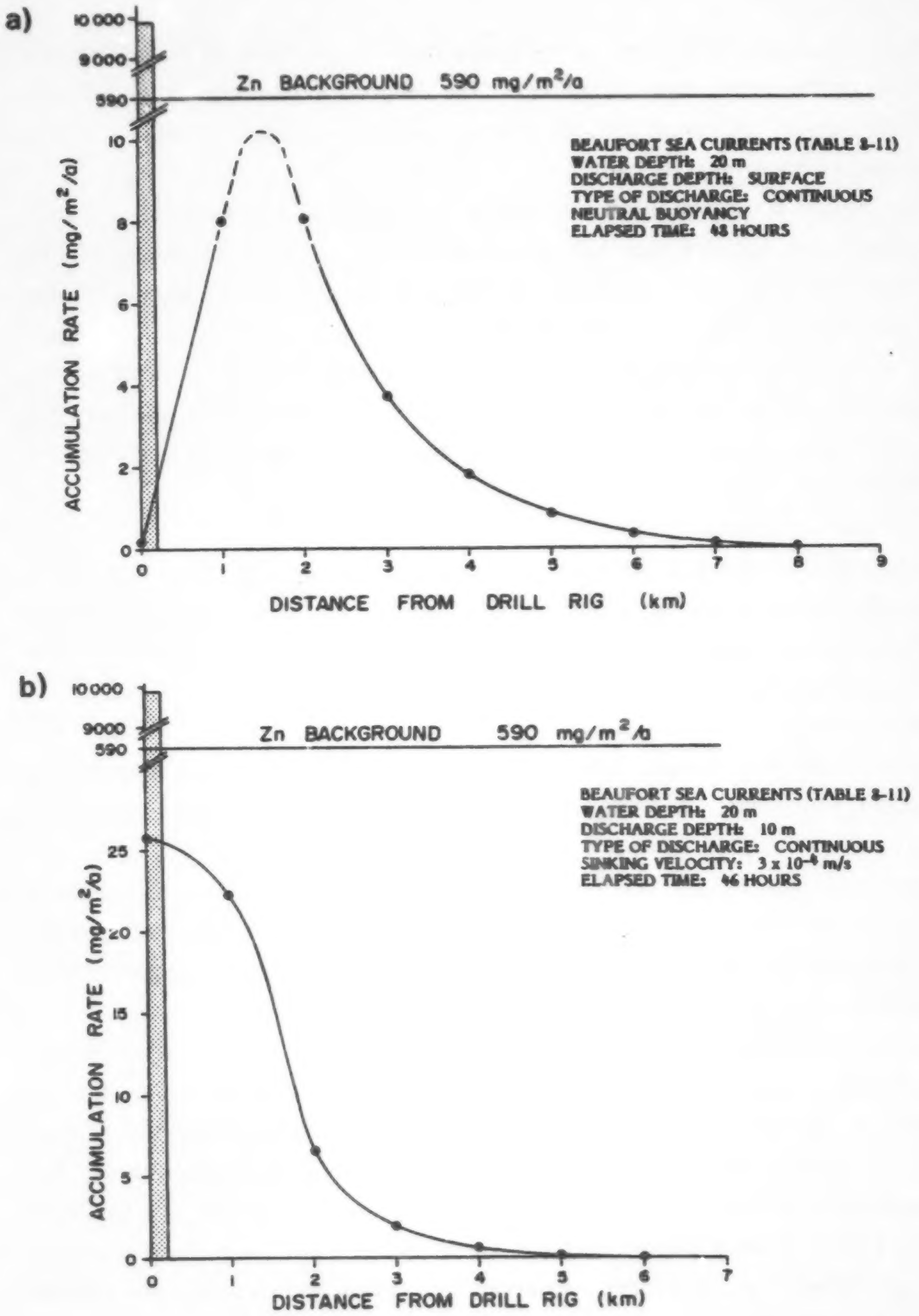

Figure 8-15. Accumulation of zinc in sediment of the Beaufort Sea down-current from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

lack of tidal influence. The shape of the curve (rate of decrease of concentration) also depends on the depth of the discharge. The deeper the discharge, the less time available for lateral transport and the greater the accumulation of metals in the sediments nearer the discharge point.

The results for the dispersion of wastes beyond 200 m of the discharge source on the Scotian Shelf indicate that background accumulation rates are exceeded only for cadmium (by factors of 6 and 20 for discharge depths 0 m and 10 m respectively at 1 km from the discharge point and approximately 4.5 and 3 for discharge depths 0 and 10 m at 5 km), and lead (at 1 km from the discharge point by a factor of 2.2 for discharge depth = 10 m) and are approximately equal for copper (at 1 km from the discharge point for discharge depth 10 m). The amount of material derived from the surface plume that settles to the bottom within 2 km of the discharge point is about 45% and 82% for surface and 10 m discharge depths, respectively.

Accumulation rates of metals from drilling fluid discharge to the Beaufort Sea beyond 200 m of the discharge point were all lower than the natural accumulation rates. About 60% and 86% of the material from the surface plume settles out within 2 km of the discharge point for surface and 10 m discharge depths, respectively.

As discussed above, the zone of influence is a relative concept. For the sake of illustration, the zone of influence could be regarded as the zone around a point source within which the accumulation rate of a component "X" from industrial activity exceeds 50% of the natural background accumulation rate for "X". Note that a different result will usually occur if the zone of influence is taken as the zone around a point source within which the concentration of a component "X" exceeds 50% of the normal background concentration of "X"; the difference is a function of the concentration of "X" in the industrial discharge.

Using the arbitrary definitions given above, the results of the dispersion model runs and the data shown in Table 7-5, approximate zones of influence were calculated for selected components of production waste discharge for the Scotian Shelf and the Beaufort Sea; the results are summarized in Tables 8-13 and 8-14. The calculations indicate that the zone of influence for cadmium on the Scotian Shelf could extend about 8 km downstream from the discharge point for surface discharge of wastes and about 6 km for wastes discharged 10 m below the surface. The zone of influence for copper on the Scotian Shelf is predicted to be about 1.5 km for wastes discharged 10 m below the surface; for lead the zones are approximately 5 km and 1.8 km for wastes discharged at the surface and 10 m depth, respectively. The zones of influence for mercury, zinc and chromium for the Scotian Shelf and all six metals for the Beaufort Sea are expected to be confined to within the 200 m zone immediately around the discharge point.

TABLE 8-13

APPROXIMATE "ZONE OF INFLUENCE"* FOR SELECTED COMPONENTS OF SCOTIAN SHELF PRODUCTION WASTE DISCHARGE AS PREDICTED BY THE DISPERSION MODEL CALCULATIONS

Element	Background Accumulation Rate	Discharge Depth	Maximum Accumulation Rate	Farthest Distance from discharge point at which accumulation resulting from industrial source exceeds 50% background rate**	Percentage increase in sediment concentration at 1, 5 and 8 kilometres from discharge point***		
	(mg m^{-2} a^{-1}) (see Table 8-12)	(m)	(mg m^{-2} a^{-1})		1 km	5 km	8 km
Cadmium	0.2	0	1.2; 0.8; 0.1	2 km; 6 km; 8 km	+ 580%	+ 420%	+ 110%
		10	4; 0.6	2 km; 6 km	+ 1925%	+ 210%	-
Chromium	650	0	30	< 200 m	+ 2%	+ 1%	+ 0.3%
		10	105	< 200 m	+ 5%	0.6%	-
Mercury	0.5	0	7	< 200 m	0	0	0
		10	25	< 200 m	0	0	-
Zinc	300	0	40	< 200 m	+ 9%	+ 7%	+ 2%
		10	140	< 200 m	+ 30%	+ 3%	-
Copper	50	0	15	< 200 m	+ 27%	+ 20%	+ 5%
		10	50	1.5 km	+ 90%	+ 10%	-
Lead	40	0	25; 20	1.2 km; 5 km	+ 65%	+ 47%	+ 13%
		10	90; 10	1.8 km	+ 215%	+ 24%	-
Hydrocarbons (as oil and grease)	250	0	750	6 km	+ 92%	+ 67%	+ 18%
		10	2600	5 km	+ 308%	+ 34%	-

* the zone of influence has been arbitrarily taken as either that zone within which the accumulation rate of "X" around a point source exceeds 50% of the natural background accumulation rate for "X" or, that zone within which the concentration of "X" around a point source exceeds 50% of the normal background concentration of "X". See text for further details.

** Obtained by inspection of Figures.

*** Calculated from model run results and data given in Table 7-5.

TABLE 8-14

APPROXIMATE "ZONE OF INFLUENCE"* FOR SELECTED COMPONENTS OF BEAUFORT SEA PRODUCTION WASTE DISCHARGE AS PREDICTED BY THE DISPERSION MODEL CALCULATIONS

Element	Background Accumulation Rate ($mg\ m^{-2}\ a^{-1}$) (see Table 8-12)	Discharge Depth (m)	Maximum Accumulation Rate ($mg\ m^{-2}\ a^{-1}$)	Farthest Distance from Discharge point at which accumulation resulting from industrial source exceeds 50% of background rate**	Percentage increase in sediment concentration at 1 km from discharge***
Cadmium	1.4	0	0.1	< 200 m	+ 7%
		10	0.3	< 200 m	+ 21%
Chromium	275	0	5	< 200 m	+ 2%
		10	16	< 200 m	+ 6%
Mercury	0.4	0	2	< 200 m	0%
		10	6	< 200 m	0%
Zinc	590	0	9	< 200 m	+ 0.8%
		10	26	< 200 m	+ 2.4%
Copper	140	0	1.1	< 200 m	+ 0.2%
		10	3.4	< 200 m	+ 0.6%
Lead	45	0	5	< 200 m	+ 11%
		10	16	< 200 m	+ 33%
Hydrocarbons (as oil and grease)	100	0	500	2.5 km	+ 28%
		10	330	1.5 km	+ 84%

* the zone of influence has been arbitrarily taken as either that zone with which the accumulation rate of "X" around a point source exceeds 50% of the natural background accumulation rate for "X" or, that zone within which the concentration of "X" around a point source exceeds 50% of the normal background concentration of "X". See text for further details.

** Obtained by inspection of Figures.

*** Calculated from model run results and data given in Table 7-5.

3.1.2 Hydrocarbons

The rate of accumulation of hydrocarbons (as oil and grease) from drilling mud and drill cuttings in the bottom sediment on the Scotian Shelf and Beaufort Sea are shown in Figures 8-16 and 8-17, respectively. The dispersion calculations indicate that production waste discharge will result in maximum rates of accumulation (at about 1 km from the discharge point) which exceed natural fluxes by factors of 3 and 9 for surface and 10 m discharge respectively. In the Beaufort Sea, the dispersed oil and grease are not expected to result in rates of accumulation which exceed natural fluxes except perhaps at approximately 2 km from the discharge point for wastes discharged at the surface.

When oil-base drilling muds are discharged to the environment, the rates of accumulation of hydrocarbons in the sediments will be greater than those indicated above; special attention must be given to those situations involving the discharge of oil-base drilling muds. Law and Blackman (1981), for example, collected sediment samples from the vicinity of three representative North Sea oil fields (Auk, Fulmar and Beryl) with the object of assessing the extent of hydrocarbon contamination from oil-base drilling muds. Auk is a producing field which was developed exclusively with water-base muds; Fulmar was not yet in production at the time of sampling but only water-base muds were used for development drilling; Beryl is a producing field and was developed extensively with oil-base muds. The results of the study indicated that hydrocarbon contamination of sediments was greater around Beryl than around Auk and Fulmar; furthermore, elevated hydrocarbon concentrations caused by the presence of drill muds and cuttings occurred to at least 18.5 km from the Beryl platform.

3.2 Sea Water

The dispersion model predicts dilution factors of at least 7 x 10^4, within a few tens of metres of the discharge pipe (see Figures 8-18, 8-19 and 8-20). This leads to an increase in ambient background of about 1 ng/L for dissolved Ni, Cd, Cu, Zn, Pb and Hg, up to 50 ng/L for dissolved Cr and about 500 ng/L for dissolved and particulate hydrocarbons (as oil and grease). These inputs are, in general, less than the natural background levels (see Tables 8-1, 8-3, 8-7 and 8-8).

In the study by Law and Blackman (1981) referred to in 3.1.2 above, most of the values obtained for the hydrocarbon content of subsurface (1 m) water samples collected around Auk, Fulmar and Beryl were similar to those regarded as background

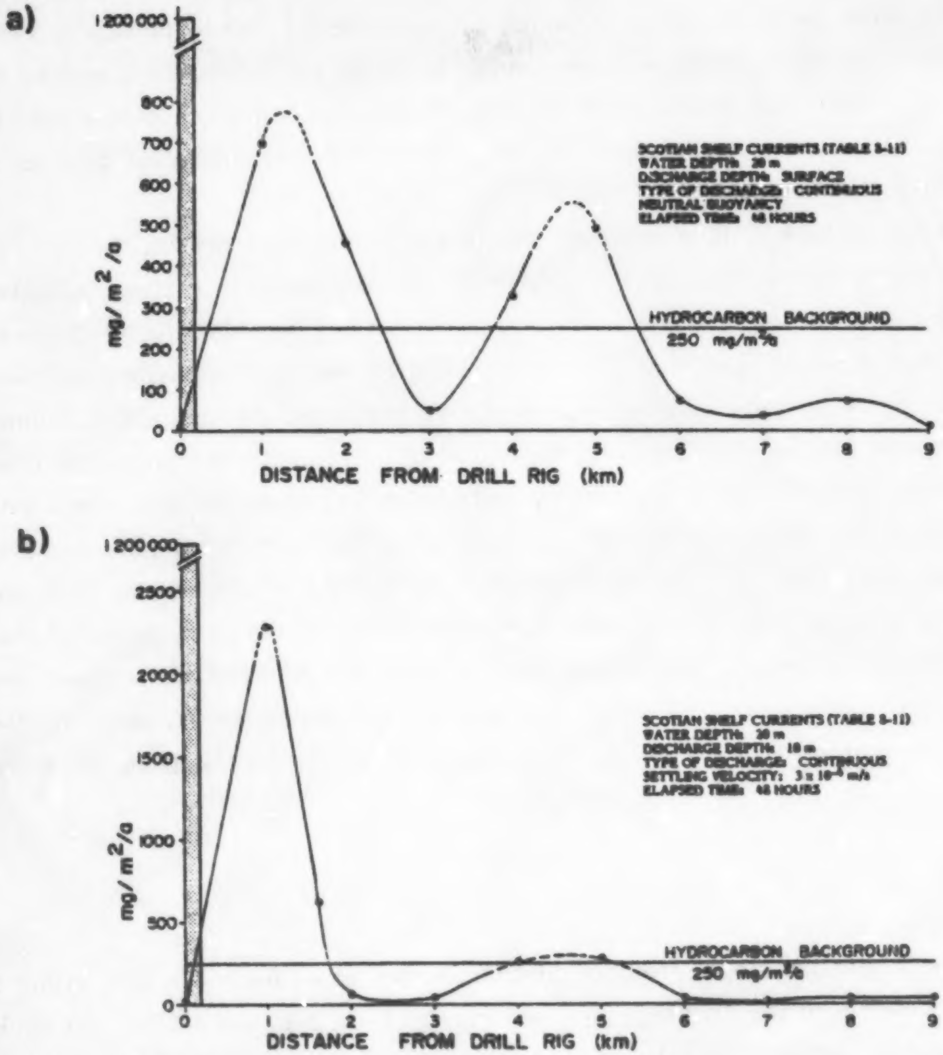

Figure 8-16. Accumulation of hydrocarbons (as oil and grease) in sediment of the Scotian Shelf downcurrent from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

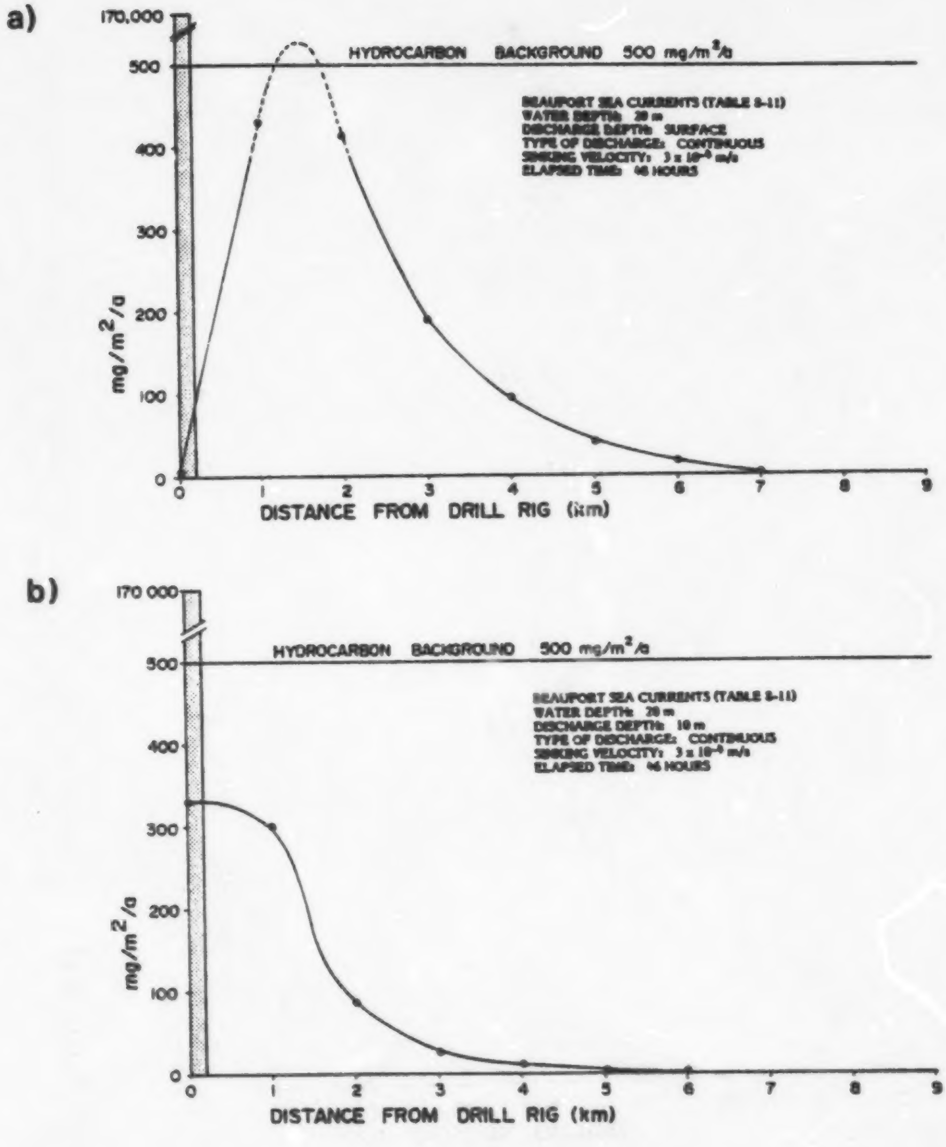

Figure 8-17. Accumulation of hydrocarbons (as oil and grease) in sediment of the Beaufort Sea Shelf downcurrent from the discharge point for (a) discharge at surface and (b) discharge 10 m below surface. The solid vertical bar along the Y axis represents the deposition of 80% of the mass of the particulate discharge within 200 metres of the discharge point (see Section 2.2.5). The natural background accumulation rate is based on the assumptions given in Table 8-12.

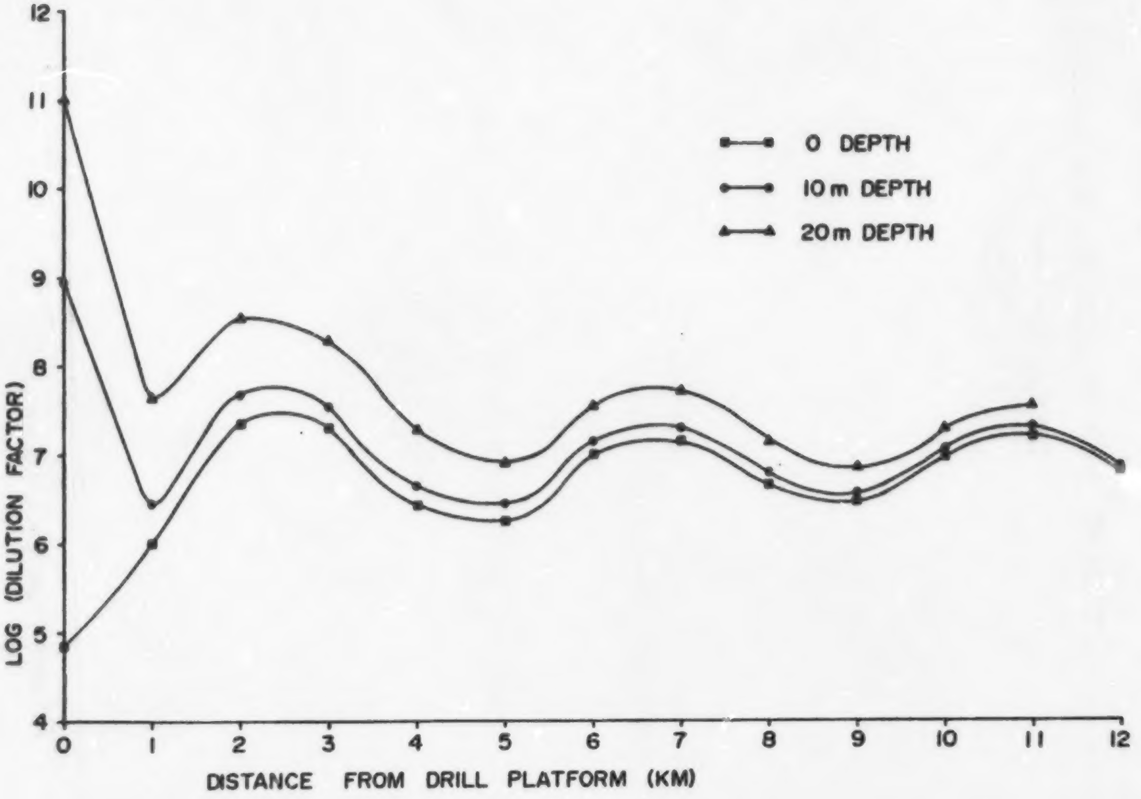

Figure 8-18. Dilution of neutrally buoyant (dissolved) wastes on the Scotian Shelf downcurrent from the discharge point.

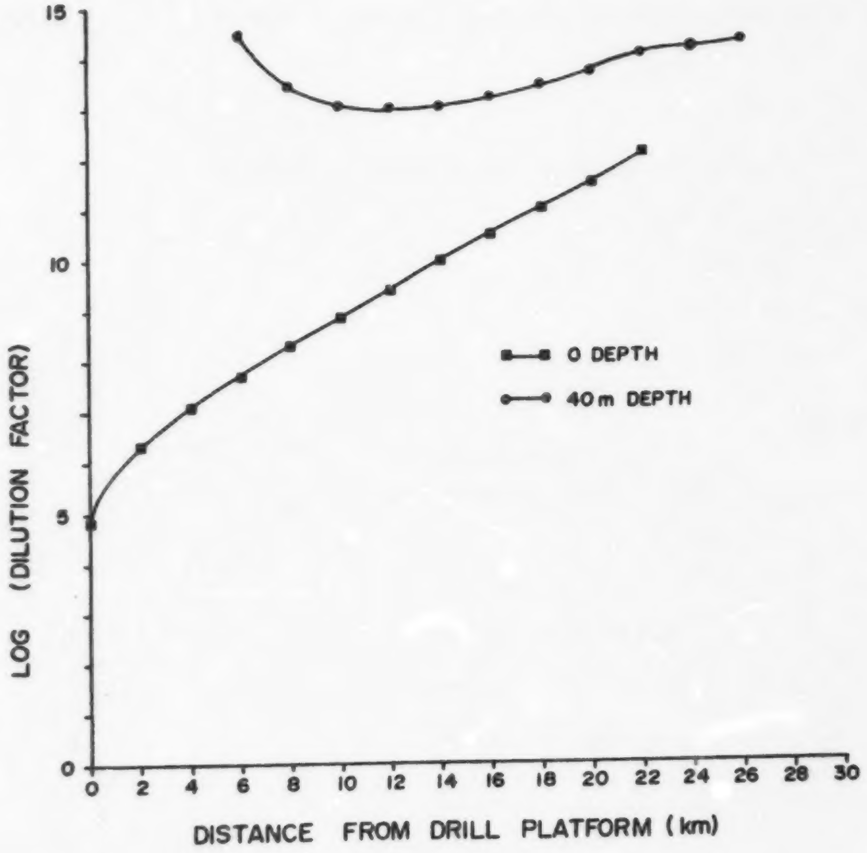

Figure 8-19. Dilution of neutrally buoyant (dissolved) wastes on the Grand Banks down-current from the discharge point.

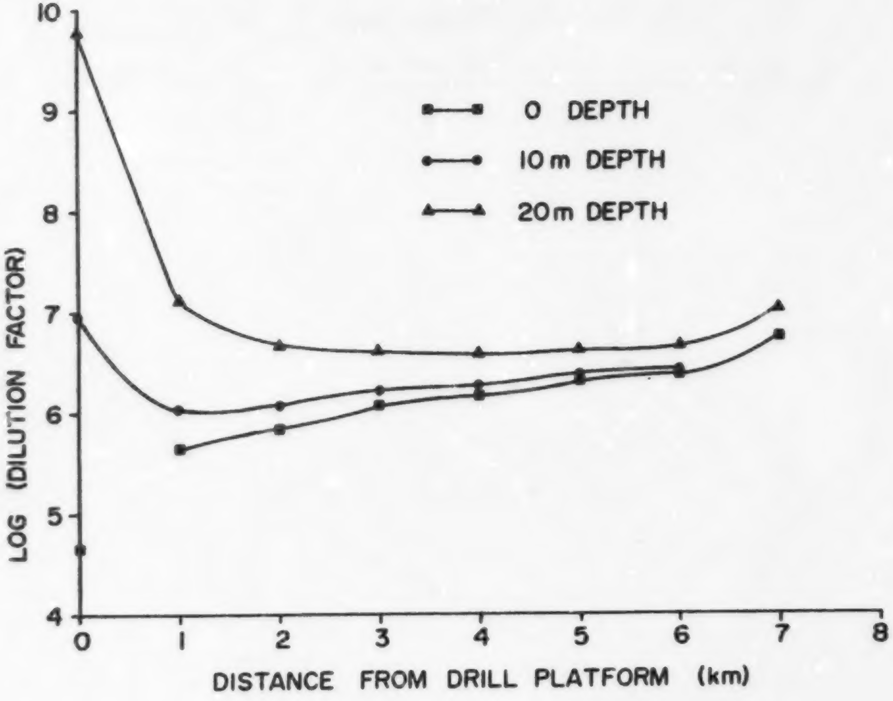

Figure 8-20. Dilution of neutrally buoyant (dissolved) wastes on the Beaufort Sea shelf down-current from the discharge point.

concentrations for these areas; consequently, there was no apparent enrichment of hydrocarbons in the water column around a site developed with oil-base mud compared to sites developed with water-base mud.

3.3 Comparison of the Dispersion Model Predictions with Field Observations of the Dispersal of Water-Base Drilling Muds and Cuttings

As stated above, the validity of results produced earlier by the dispersion model have not been verified by any direct experimental measurements. The dispersion of water-base drilling muds and cuttings from offshore oil exploration and production platforms in various parts of the world, however, has been the subject of many field and experimental studies. The results of these studies are in general agreement with the prediction of the dispersion model used in this study that the zone of influence around a point discharge is usually limited to distances of hundreds of metres or a few kilometres.

Discharges of waste water-base drilling muds and cuttings from offshore platforms can be classified as being either bulk discharges or continuous discharges. Bulk discharges usually involve high rates of discharge for short periods of time whereas continuous discharges usually involve low rates of discharge for extended periods of time. For the Canadian production scenarios in the three offshore regions, bulk discharges of approximately 100 m^3, one to six times during the life of a well, are expected (see Table 7-5). The combined continuous discharge of drilling muds and cuttings is expected to be in the range of 14 m^3/d to 130 m^3/d depending on the type of mud used and the well depth (see Table 7-5). An approximate average value would be 50 m^3/d or 2 m^3/hour.

3.3.1 Bulk Discharges

The dilution and fate of two experimental bulk discharges of drilling mud from an exploratory rig in the Gulf of Mexico was reported by Ayers et al. (1980 b). The first bulk discharge was 40 m^3 drilling mud discharged at a rate of 44 m^3/h; the second involved 62 m^3 drilling mud discharged at 160 m^3/h. For both discharges, dilution of the mud solids to background concentrations occurred within 1000 metres downcurrent from the discharge point and was accomplished within less than two hours. In another study conducted by Ayers et al. (1980 c) around an offshore platform off the East Coast of the United States, background concentrations of suspended solids were reached within about 350 metres of the discharge source during an 80 m^3/h discharge of drilling mud.

Measurements made during low volume bulk discharges from a platform on the Tanner Bank (Ecomar, Inc. 1978) indicated that background conditions in suspended particulate matter concentrations were generally achieved within 90-200 metres of the discharge point for discharge rates of 2 to 4 m^3/hour. Initial dilution was very high, perhaps 1000:1 within several metres of the discharge point. Additional evidence for large and rapid dilution of discharged drilling wastes is given by Zingula (1975) whose results indicate that drilling muds and cuttings discharged from a platform in Timbalier Bay, Louisiana may be diluted approximately 1000 fold in the discharge pipe before actual discharge to the ocean.

Thomas (1979 c) studied the dispersion of a bulk discharge of drilling mud at the Nerlerk M 98 exploratory well in the Beaufort Sea. Approximately 40 m^3 of drilling mud was discharged at the rate of 120 m^3/h; at 50 metres from the discharge point 10 minutes after discharge ceased the suspended particulate matter concentrations were only slightly elevated relative to background and indicated dilution factors of about 10^5.

3.3.2 Continuous Discharges

Houghton et al. (1980) measured the dilution and dispersion of a continuous discharge of drilling mud and cuttings from a drilling platform in Cook Inlet, Alaska; the drilling wastes were discharged at the rate of 3.2 m^3/h for 24 hours. Using Rhodamine WT dye as a tracer, they determined that dilutions of about 10^4 were achieved within about 100 metres (or a few minutes) of the discharge. It should be noted that in the above investigation the continuous discharge was only for a 24 hour period; in general, there is a lack of field measurements of the dispersion of drilling muds and cuttings from a continuous point source discharge.

4.0 Biological Concerns

4.1 Production Wastes of No Significant Biological Concern

As indicated earlier in Chapter 5, the majority of wastes associated with offshore oil and gas production are either liquids discharged on an intermittent basis in relatively small amounts and subsequently diluted to non-toxic concentrations within a few metres of outfalls, or solids which rapidly settle to the seafloor near production facilities and only have highly local impacts on marine fauna. Wastes included in this category are not of significant biological concern in any of the potential Canadian offshore production regions, and are therefore briefly mentioned in the present section prior to discussion of concerns related to offshore production on the Scotian Shelf and Grand Banks, and in the Canadian Beaufort Sea. As shown in Table 8-15, the primary reason for the limited biological concern with the majority of production wastes is either the small zone of influence or total loading expected for these wastes.

4.2 Scotian Shelf

After the application of current waste treatment practices, three remaining concerns with respect to production waste effects on the biological communities of the Sable Island Bank are:

- chronic introduction of oil from produced water discharges;
- long-term, local trace metal loading from discharged produced waters;
- local metal and petroleum hydrocarbon loading from discharged drilling fluids and oil-contaminated cuttings

The concerns are listed in Table 8-16 and include in point form the justification for the concern and a presentation of the factors that entered into the decision to highlight the particular waste for this geographical region. The factors are generally drawn from considerations of the development drilling and projected production wastes on the Scotian Shelf (Chapter 7, Sections 1.2 and 3.0), the nature of the receiving environment (Chapter 7, Sections 2.1, 2.2), the expected zones of influence of specific wastes (Chapter 8, Section 2.2.5, 3.1.1, 3.1.2) and the biological effects information summarized in Chapter 5.

TABLE 8-15

OIL AND GAS PRODUCTION WASTES OF LIMITED BIOLOGICAL CONCERN FOR ALL OFFSHORE CANADIAN REGIONS

WASTE	RATIONALE	SECTION
Cuttings from drilling operations utilizing water-base drilling fluids	• accumulation of cuttings and heavier solids in drilling fluids is typically restricted to an area within 300m of discharge sites, but may extend up to 1000m from a platform depending on water depth, depth of discharge and currents.	Chapter 5 Section 2.1.5
	• biological effects are limited to direct smothering proximate to discharge sites and potential alteration of sediment composition beyond the cuttings piles.	Chapter 5 Section 2.1.5
	• recolonization of cuttings piles and adjacent areas occurs relatively soon after drilling ceases.	Chapter 5 Section 2.1.5
Well Completion and Workover Fluids	• discharge of completion fluids occurs only once during the life of a well, while workover fluids may be discharged several times during the life of a well.	Chapter 2 Section 6
	• both completion and workover fluids permeate the formation, most acids are spent, and any remaining fluids drawn out of the formation are diluted in the produced water waste stream and discharged as a slug.	Chapter 2 Section 6
	• dilution of anions and cations (the primary concerns are zinc and bromide) would occur within a few metres of discharge sites.	Chapter 5 Section 2.3
	• although ionic zinc is moderately to highly toxic to marine organisms, concentrations would be reduced to levels well below those known to cause adverse effects (0.1-200 ppm) rapidly upon discharge with the produced water waste stream, and therefore adverse impacts would be both short-term and localized.	Chapter 5 Section 2.3
BOP Control Fluid	• BOP control fluid is only released on an intermittent basis (daily to weekly) during the testing of seafloor-mounted BOP stacks, and this testing only occurs during the period of development drilling.	Chapter 5 Section 2.4
	• the total amount of control fluid released during each test is relatively small (0.2-1.0 m^3), and this fluid would tend to sink to the seafloor prior to dispersion/dilution due to its high specific gravity.	Chapter 2 Section 6.4
	• Ethylene glycol, a major constituent of BOP control fluids used in Canada, is moderately toxic (LC_{50}: 100-1000 ppm) to some fauna and also has a high oxygen demand, although natural dilution would reduce concentrations to non-toxic levels within a few meters of BOP stacks.	Chapter 5 Section 2.4
	• microbial degradation of glycols would also prevent accumulation or persistence of this waste in marine environments.	Chapter 5 Section 2.4
Cement Slurry	• small volumes (3-25 m^3/well) of excess cement are only discharged during grouting of the riser and the upper casings at the seafloor during drilling.	Chapter 2 Section 6.5
	• biological effects would be largely restricted to smothering of benthic infauna and sessile epifauna proximate to the discharge point, and short-term and very localized effects on other benthic and near bottom communities resulting from pH-related toxicity of calcium oxide and calcium hydroxide.	Chapter 5 Section 2.5

TABLE 8-15 (cont'd)

OIL AND GAS PRODUCTION WASTES OF LIMITED BIOLOGICAL CONCERN FOR ALL OFFSHORE CANADIAN REGIONS

WASTE	RATIONALE	SECTION
Produced Sand	· the total quantity of produced sand released to the marine environment may range from one to 40 m^3 per day although treatment generally reduces the oil content to a low level	Chapter 2 Section 4
	· the chronic introduction of oil associated with produced sand would be a very small proportion of the total oil input resulting from discharge of offshore production wastes (particularly produced water)	Chapter 5 Section 4
	· deposition of sand in benthic habitats, and subsequent effects on fauna would be restricted to areas within a few hundred metres of discharge sites, and turbidity-related effects on planktonic/nektonic organisms would also be localized	Chapter 5 Section 4
Treated Sewage and Domestic Waste	· the overall volume of sanitary and domestic wastes discharged from production platforms is relatively small, and may typically average 5 m^3 of sewage and 10 m^3 of domestic waste per day. Sewage effluent undergoes secondary treatment.	Chapter 2 Section 7
	· any effects associated with nutrient enrichment, oxygen depletion, smothering of benthos, and toxicity of residual chlorine would be restricted to the immediate vicinity of outfalls.	Chapter 5 Section 5
Gas and Oil Processing Wastes	· only small quantities of these wastes are released to the marine environment	Chapter 2 Section 8
	· most of the chemicals are not highly toxic to marine organisms, and some (e.g. alcohol solvents and glycols) are rapidly biograded; addition of phosphate esters and amines could locally increase primary production, while reduction of amines to ammonia could cause local toxic effects.	Chapter 5 Section 6
	· any adverse effects of gas and oil processing wastes would be very localized due to rapid natural dispersion and dilution of these compounds in offshore environments.	Chapter 5 Section 6
Ballast Water	· assuming that tankers with segregated ballast compartments are employed in future Canadian offshore oil production regions, discharge of oil contaminated ballast is not an environmental concern.	Chapter 5 Section 3
	· when empty cargo tanks must be ballasted to provide additional stability in high seas, the ballast would be treated before discharge. The need for this ballasting should be infrequent.	Chapter 7 Section 3
	· treated ballast would typically contain 10 mg/L total oil and 5 mg/L aromatics, and under the abnormal situation indicated above, typical discharge rates would range from 10,000 to 50,000 m^3/day (max: 100,000-200,000 m^3/day).	Chapter 2 Section 3
	· the daily oil loading to the marine environment under these abnormal circumstances would range from 100 to 2000 kg, and this infrequent loading would be a small proportion of the total hydrocarbon input associated with more continuous produced water discharges.	
Storage Displacement Water	· only about 10 percent of the total volume of storage displacement water discharged (max: 12,000-48,000 m^3/day) would require treatment due to contamination of displacement water at the oil-water interface; a small proportion of the oil in storage displacement water would be aromatic hydrocarbons (compared to ballast water)	Chapter 2 Section 3
	· oil input to the marine environment from this source would be restricted to periods of tanker loading, and would only average 12 to 48 kg/day during these periods.	
	· the biological effects of this quantity of chronic oil discharge would be largely indistinguishable from other sources of oil loading such as deck washing and produced water discharge.	Chapter 5 Section 3

TABLE 8-16

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE SCOTIAN SHELF

WASTE	EVALUATION OF CONCERNS	CROSS-REFERENCES
Produced Water	. produced water for Scotian Shelf production areas will be discharged at rates less than or equal to those of of other production fields throughout the world. Data reported for other production fields, are expected to apply to the Sable Island Bank area.	Table 7-4 Chapter 5, Section 1.2
	. water column biota are not a concern because: i) predicted dilution of produced waters throughout the water column is about x 10^6 (except for surface water discharge) within 1 km of the discharge point; ii) produced waters are acutely lethal to biota at concentrations 3-4 orders of magnitude greater than those predicted for the Scotian Shelf; iii) the small volume of sea water containing produced waters that could be toxic would only affect a small proportion of planktonic and nektonic populations in an open water system.	Figure 8-15 Chapter 5, Section 1.1
	. there should be no lethal toxicity to benthic biota because: i) the produced water will be diluted to concentrations several orders of magnitude below those that are acutely lethal in bioassay tests;	Figure 8-15 Chapter 5, Section 1.1
	ii) "worst-case" produced water exposure regimes for benthic species at a particular point will be substantially less than those demonstrated to produce lethal or sublethal responses in marine benthic species.	Figure 8-15 Chapter 5, Section 1.1
	. metal accumulation from produced waters by biota has not been conclusively established or disproven. The potential is probably restricted to sessile organisms in the immediate vicinity of the discharge. On the shallows of the Sable Island Bank, permanent, sessile infauna are not a prominent feature because of the shifting sand bottom.	Chapter 5, Section 1.2.1

TABLE 8-16 (Cont'd)

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE SCOTIAN SHELF

WASTE	EVALUATION OF CONCERNS	CROSS-REFERENCES
Water-Base Muds	. likely discharge rates of water-base muds on the Scotian Shelf are similar to rates for other North American locations. Monitoring data from these areas are deemed to be applicable to the Scotian Shelf.	Table 7-5 Table 2-10, 2-11
	. lethal effects are not a concern because: i) direct burial of biota is limited to a zone in the immediate vicinity of the discharge; ii) dilution will reduce mud concentrations to several orders of magnitude less than those known to be acutely lethal.	Chapter 5, Section 2.1.3, 2.1.5
	. as sublethal effects have only been detected at mud concentrations near those that are acutely lethal, sublethal toxicity from the mud is not a present concern	Chapter 5, Section 2.1.2
	. long-term biological effects as a result of loading from some metals in sediments remains a concern because of predicted deposition of Cd and Pb to sediments beyond the discharge zone rates greater than natural input rates and occasional records of metal bioconcentration around drilling sites. Levels of accumulation would probably not pose a hazard to humans consuming fish but their effects on the biota are uncertain.	Figures 8-7, 8-8 Table 5-8 Chapter 5, Section 2.1.4 and 2.1.5
Water-Base Muds	. loadings from closely situated multiple discharge sources (1-3 discharges within 5 km of each other) are of concern with respect to cadmium, lead and copper. Biological concerns are similar to those for single discharge.	Chapter 8, Section 3.1.2

TABLE 8-16 (Cont'd)

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE SCOTIAN SHELF

WASTE	EVALUATION OF CONCERNS	CROSS-REFERENCES
Diesel Oil Contaminated Cuttings	• the input of oil associated with cleaned cuttings is of substantial concern because of: i) the large amount of oil, including toxic aromatics, which adheres to the cuttings; ii) the high toxicity of diesel oil-base muds; iii) the demonstrated accumulation and probable persistence of the aromatics in the diesel oil sediments around producing fields where they have been used; iv) the smothering effect of the material on bottom communities where bottom wave or current energy is insufficient to rapidly disperse the cuttings	Chapter 2, Section 2.3.4 Chapter 5, Section 2.2
Paraffin Oil Contaminated Cuttings	• substitution of paraffin oil for diesel oil in mud systems reduces the concern for lethal toxicity associated with diesel oil. Cuttings can still act to smother benthic communities in immediate vicinity of discharge, although total oil discharged is less with paraffin cuttings than with diesel cuttings, for similar levels of cuttings cleaning.	Chapter 5, Section 2.2.1 Chapter 2, Table 2-19
	• similar aromatic contents in diesel (20-30%) and paraffin oils (5-20%) are a concern. The absence of 1 and 2 ring aromatics in paraffin oils probably accounts for the substantial differences in their toxicities. Persistence of polynuclear aromatic hydrocarbons associated with paraffin muds is of concern in the benthic environment because of their persistence and demonstrated carcinogenicity of some of these compounds.	Chapter 2, Section 2.3.3, 2.3.4
Exotic Chemicals	• the introduction of exotic (man-made) chemicals is an area of concern because of (1) the high toxicity of some chemicals (e.g., biocides) to marine fauna, and (2) the demonstrated persistence and bioaccumulation of halogenated organics in marine ecosystems.	Chapter 5, Section 2.1.1

The concerns stem more from uncertainties about the generalized exposure/response relationships between specific wastes with their constituent metal or petroleum hydrocarbon contents and types of biological communities, rather than from unique biological features of the receiving environments on the Sable Island Bank. The same general basis for the identification of biological concerns applies to the northeastern Grand Banks and Beaufort Sea.

A number of the concerns identified derive from model predictions of increased chemical loading to the sediments of Sable Island Bank. The model is based on dispersion and diffusion leading to dilution in the water column. Sediment dynamics are not considered in the loading calculations and the loadings and zones of influence therefore represent worst-case conditions. The Sable Island Bank is a dynamic sedimentary environment where the presence of sand and coarser material suggest the continued reworking of sediments and winnowing of finer-grained material for transport to depositional sinks for this material in deeper waters. It therefore appears likely, but not proven, that sediment reworking and transport will probably disperse the metals and petroleum hydrocarbons deposited into the sediments from production wastes. This factor, if correct, should eliminate metal loading concerns but does not remove the underlying concern for the introduction of aromatic hydrocarbons into the sedimentary environment of the Sable Island Bank where groundfish are the major fish species.

4.3 Grand Banks

Substantially greater dilution of discharged substances within the same areas can probably be achieved on the northeastern Grand Banks than in the two other production areas under consideration. The enhanced dilution will be facilitated by greater water depths on the Grand Banks site and different water circulation and mixing characteristics. Dilution of neutrally buoyant discharges (model assumption for produced waters) is sufficient to reduce discharged substances to negligible concentrations before they reach the bottom (Figure 8-19). The portion of waste drilling fluids that initially stays in the water column is diluted rapidly enough to result in no significant input of fine particulate material to the sediments. This factor suggests that there should be little if any incremental loading of chemicals associated with drilling fluids to sediments outside of the immediate mud solids dump locations. With these characteristics of the physical environment in mind, the remaining biological concerns for the Grand Bank include:

- chronic oil introduction into the marine ecosystem derived from produced waters;
- local effects of diesel or paraffin oil contaminated cuttings and formation crude contaminated cuttings with multiple field development.

Table 8-17 summarizes the considerations that led to the identification of these concerns, drawn from descriptions of the probable production scenario for the Grand Banks (Chapter 7, Section 1.3 and 3.0), the expected zones of influence of specific wastes (Chapter 8, Section 2.2.5, 3.1.1, 3.1.2), and the summarized fate and effects information in Chapter 5.

TABLE 8-17

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE NORTHEAST GRAND BANKS

WASTE	EVALUATION OF CONCERNS	CROSS-REFERENCES
Produced Water	. produced water for Grand Banks production areas will be discharged at rates similar to those of other offshore fields throughout the world.	Table 2-1 Table 7-4
	. water column biota are not a concern because of the predicted substantial and rapid dilution reducing produced water concentrations to less than 1 ppm at any distance greater than 2 km and probably less than that away from the discharge source. These concentrations are substantially less than those which are acutely toxic to biota	Figure 8-16 Chapter 5, Section 1.1
	. residual aromatic hydrocarbon loading to the environment remains a concern because of the volumes of produced water and persistence of aromatics once in the sedimentary environment. Although input to the benthic system is not predicted by the model, the introduction of aromatics is of concern because of the chronic effects of these compounds. Petroleum contamination of biota, along with histopathological and biochemical effects in some biota in producing fields, suggests that this aspect of produced water disposal may be of concern on the Grand Banks.	Chapter 2, Section 1.4 Chapter 5, Section 1.2.2
Diesel Oil Contaminated Cuttings	. The input of oil associated with cleaned cuttings is of substantial concern because: i) the large amount of oil, including toxic aromatics, which adheres to the cuttings; ii) the high toxicity of diesel oil-base muds; iii) the demonstrated accumulation and probable persistence of these aromatics in sediments around producing fields where they have been used; iii) the smothering effect of the material on bottom communities where bottom wave or current energy is insufficient to disperse the cuttings rapidly.	Chapter 2, Section 2.3.4 Chapter 5, Section 2.2

TABLE 8-17 (Cont'd)

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE NORTHEAST GRAND BANKS

WASTE	EVALUATION OF CONCERNS	CROSS-REFERENCES
Diesel Oil Contaminated Cuttings (cont'd)	. the presence of fine-grained sediments at depths greater than about 120 m on the northeastern Grand Gank suggests that bottom currents would be too weak to move cuttings from their depositional sites	
Paraffin Oil Contaminated Cuttings	. substitution of paraffin oil for diesel oil in mud systems reduces the concern for acute lethal toxicity associated with diesel oil. Cuttings can still act to smother benthic communities in the immediate vicinity of discharge, although total oil discharged is less with paraffin cuttings than with diesel cuttings.	Chapter 5, Section 2.2.1 Chapter 2, Table 2-19
	. similar aromatic contents in diesel (20-30%) and paraffin oils (5-20%) are a concern. The absence of 1 and 2 ring aromatics in paraffin oils probably accounts for the substantial differences in their toxicities. Persistence of polynuclear aromatic hydrocarbons aromatics associated with paraffin muds is of concern in the benthic environment because of the persistence and demonstrated carcinogeneicity of some of these compounds.	Chapter 2, Section 2.3.3, 2.3.4
Exotic Chemicals	. the introduction of exotic (man-made) chemicals is an area of concern because of (1) the high toxicity of some chemicals (e.g., biocides) to marine fauna, and (2) the demonstrated persistence and bioaccumulation of halogenated organics in marine ecosystems.	Chapter 5, Section 2.1.1

4.4 Beaufort Sea

The primary biological concerns associated with offshore oil and gas production in the Beaufort Sea are:

(a) chronic introduction of oil resulting from produced water discharge (and to a lesser extent deck drainage);

(b) long-term but local trace metal loading;

(c) local effects of drilling fluid and formation cutting discharge; and

(d) the possible introduction of persistent man-made chemicals throughout development drilling and production.

Potential effects of oil introduced to the marine environment through the discharge of formation-oil contaminated cuttings and discharge of cuttings containing either diesel or paraffin oil from use of an oil-base drilling mud formulation, would also be an area of significant but local biological concern. Much of the concern regarding the potential effects of produced water and drilling wastes is due to the lack of convincing evidence that marine fauna do not accumulate aromatic hydrocarbons and certain trace metals from these wastes (see also Section 4.2). From a regional perspective, direct mortality of marine organisms would not be a significant concern in the Beaufort Sea or elsewhere (see Table 8-18).

TABLE 8-18

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE CANADIAN BEAUFORT SEA

WASTE	RATIONALE	REFERENCE
Produced Water	. the effects of produced water on planktonic/nektonic organisms are not a concern because: (1) predicted dilution of produced water throughout the water column is greater than a factor of 5×10^5, except within 1 km of discharge sites, although the maximum zone of influence may extend up to 7 km from discharge sites, (2) acute toxic effects would only be expected at concentrations of produced water which are several orders of magnitude higher than those expected only a few metres from discharge sites, and (3) an extremely small proportion of planktonic and nektonic organisms in the region would actually be exposed to produced water, particularly during the winter (ice-covered) months	Chapter 8, Section 3.3.1 Chapter 5, Section 1.1
	. the effects of produced water on epontic (under-ice organisms) are a concern because (1) there could be a tendency for produced water to become trapped (and possibly encapsulated) in irregularities in the under-ice surface, (2) this could result in persistent or repeated exposure of organisms under landfast ice to produced water, or contamination of relatively extensive areas of moving transition ice (depending on the location of production platforms in relation to the location of these zones, which also varies annually), (3) exposure of epontic flora and fauna to produced water for periods ranging from several days to a few weeks could result in acute lethal effects and sublethal effects including trace metal and aromatic hydrocarbon accumulation, (4) the epontic community is not only expected to contribute an unknown but significant amount to the annual primary productivity of the region, but is important to the development of both planktonic and benthic communities in the spring, and (5) indirect impact on other organisms which are expected to feed on epontic fauna (e.g., arctic cod, ringed seal) are considered possible, including biomagnification of certain heavy metals.	Chapter 5, Section 1.1 Dome Petroleum et al. (1982)

TABLE 8-18 (Cont'd)

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE CANADIAN BEAUFORT SEA

WASTE	RATIONALE	REFERENCE
Produced water (cont'd)	. there should be no mortality of benthic organisms due to produced water exposure because produced water is expected to be diluted to concentrations several orders of magnitude below those shown to be acutely toxic in bioassay tests, within a few metres of discharge sites. The effects of produced water on benthic organisms is still a concern because (1) the potential for accumulation of trace metals and petroleum hydrocarbons from produced waters has not been conclusively disproven and (2) the duration of exposure of sessile infauna and epifauna to this waste would be long-term. Since production platforms (islands) in the Beaufort Sea would be located on a subsea berm constructed of coarser granular materials and rock, organisms colonizing these structures and therefore most susceptible to produced water exposure would likely include species which are not abundant in the generally silt substrate habitats which predominate in this region. This is expected to reduce any regional significance of potential effects of produced water on benthic biota	Chapter 8, Section 3.3 Chapter 5, Section 1.1 Dome Petroleum *et al.* (1982)
	. The primary area of concern related to the effects of produced water on benthic communities is the residual hydrocarbon loading to the benthic environment, and the persistence of aromatics in the sedimentary environments which are characteristic of the region. The relatively high suspended sediment levels in the water column during the open-water season could favour the transport of any particulate oil (e.g. dispersed oil in deck drainage) to the sediments through adsorption. Studies conducted in areas of offshore oil production in the Gulf of Mexico have not correlated hydrocarbon levels in sediments and tissues of biota in a consistent manner, although histopathological and biochemical effects have been reported in some areas. The chronic effects and ecological significance of long-term exposure to petroleum hydrocarbons remain unknown. The degree of concern associated with effects of produced	Chapter 7, Section 2.1 Chapter 5, Section 1.2.2

TABLE 8-18 (Cont'd)

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE CANADIAN BEAUFORT SEA

WASTE	RATIONALE	REFERENCE
Produced Water (cont'd)	water on benthic (and epontic) biota is increased by the shallow water depths, ice cover for eight months of the year and low under-ice currents which could all limit dilution and dispersion of produced water	
Water-Base Muds	. the effects of water-base drilling muds on planktonic, nektonic and epontic organisms are not a concern because (1) this waste is expected to be diluted to concentrations well below those shown to cause acute lethal and sublethal effects within a few metres of discharge sites, (2) an extremely small proportion of planktonic and nektonic organisms in the region would actually be exposed to water-base drilling fluids, particularly during the winter months, and (3) the tendency of suspended fines to settle out downstream of discharge sites would minimize exposure of epontic organisms to drilling muds in the winter, particularly if wastes were shunted to mid-depth or bottom	Chapter 8, Section 3.3.1 Chapter 5, Section 2.1 Chapter 8, Section 3.3.2
	. the effects of water-base drilling muds on benthic biota are a local concern because (1) direct burial of fauna would be limited to a zone in the immediate vicinity (<1 km) of discharge sites, and (2) metal loading to the sediments beyond the primary zones of solids deposition (within 400 m) is expected to be 1-2 orders of magnitude less than natural input rates to this region. Occasional records of metal bioaccumulation in areas of drilling mud disposal suggest that uptake of Cr, Cd, Pb and Hg may occur within 400 m of discharge sites. Levels of accumulation by benthic fauna are unlikely to pose a hazard to humans consuming fish but the long-term effects of this uptake on biota are unknown.	Chapter 5, Section 2.1.4

TABLE 8-18 (Cont'd)

BIOLOGICAL CONCERNS RELATED TO OFFSHORE OIL AND GAS PRODUCTION WASTE DISCHARGE TO THE CANADIAN BEAUFORT SEA

WASTE	RATIONALE	REFERENCE
Diesel Oil Contaminated Cuttings	• If diesel-base drilling fluids were used in the offshore Beaufort Sea, the effects of diesel-contaminated cuttings on all classes of marine biota would be a significant regional concern because of (1) the large amount of oil, including toxic aromatics, which adheres to cuttings even after cleaning, (2) the high toxicity of diesel oil-base drilling muds, (3) the demonstrated accumulation and probable persistence of aromatic hydrocarbons in sediments around production fields where diesel-base muds have been used, and (4) the smothering effect of this material on benthic communities in areas where water circulation is insufficient to rapidly disperse the cuttings.	Chapter 2, Section 2.3.4 Chapter 5, Section 2.2
Paraffin Oil Contaminated Cuttings	• the substitution of paraffin oil for diesel oil as a carrier in oil-base mud systems substantially reduces the toxicity of these systems because of the absence of 1- and 2-ring aromatics in paraffin oils. The effects of paraffin-oil contaminated cuttings on benthic biota are still a local concern because (1) the cuttings and associated oil can smother benthic organisms in the immediate vicinity of discharge sites (despite the fact that the total amount of oil discharged with cuttings is less with paraffin-based muds), and (2) persistence of 3- and greater ring (polynuclear aromatic hydrocarbons) aromatics associated with paraffin-based muds in benthic environments and the demonstrated carcinogenic nature of some of these compounds.	Chapter 5, Section 2.2.1 Chapter 2, Table 2-19 Malins (1977)
Exotic Chemicals	• the introduction of exotic (man-made) chemicals is an area of concern because of (1) the high toxicity of some chemicals (e.g., biocides) to marine fauna, and (2) the demonstrated persistence and bioaccumulation of halogenated organics in marine ecosystems.	Chapter 5, Section 2.1.1

5.0 Environmental Significance

5.1 Mass Loadings

Table 8-19 compares the estimated future mass loadings of metals and hydrocarbons to the Scotian Shelf, Grand Banks and Beaufort Sea from offshore oil and gas waste discharges with data for mass loadings to existing offshore production areas. Natural budgets for metals and hydrocarbons have been calculated recently for the Beaufort Sea (Thomas et al. 1983) but are not available for the Scotian Shelf or the Grand Banks. In the example of the Beaufort Sea, the natural flux of metals to the shelf would exceed the anticipated anthropogenic flux of metals from the hydrocarbon development activities by a factor of 10^3 to 10^4. A smaller natural flux would be expected for the Scotian Shelf and Grand Banks; a reasonable expectation would be for natural metal fluxes to exceed anthropogenic fluxes by 10^2 to 10^3. For hydrocarbons, the budget calculations for the Beaufort Sea indicate that the annual natural flux would exceed the anthropogenic flux by about an order of magnitude. One would speculate that this would probably also be the case for the Scotian Shelf and Grand Banks areas.

5.2 Factors Affecting the Estimation of Mass Loading

The results of the dispersion model were obtained by assuming that the dispersed material settled out in a random omni-directional pattern. This simplifying assumption was made because no specific data were available to determine direction of dispersion. However, this would seldom, if ever, occur. A reasonable assumption is that currents flow consistently within an arc of 60°. In this situation, the accumulation rates in sediments would be six times those calculated and shown in Figures 8-4 to 8-17. These rates would still be well below the natural accumulation rates for all metals except copper, lead and zinc on the Scotian Shelf, and Cd and Pb on the Beaufort Sea Shelf.

Another situation that would increase the rate of accumulation of disposed material in the sediments would be overlapping discharges from several drilling platforms. Assuming that a field is developed by a cluster of three drilling platforms about 8 km from each other, the closest and most intense zone of overlap would be 4 km downstream from the discharge. At 4 km, the accumulation rates would be sufficiently small that even a complete overlap by the discharges from all three platforms would only triple the maximum accumulation rate predicted by the model.

TABLE 8-19

COMPARISON OF MASS LOADINGS OF METALS AND HYDROCARBONS TO EXISTING OFFSHORE PRODUCTION AREAS WITH ESTIMATED FUTURE LOADINGS TO CANADIAN OFFSHORE AREAS

COMPONENT	UNITS	U.K. NORTH SEA	NORWEGIAN SHELF	GULF OF MEXICO	SCOTIAN SHELF (4)			GRAND BANKS (4)			BEAUFORT SEA (4)			
					Drilling Fluids	Produced Water	Total	Drilling Fluids	Produced Water	Total	Drilling Fluid	Produced Water	Total	Natural Annual Flux (6)
METALS														
Chromium	kg	-	-	2.1×10^6 (3)	7.9×10^3	6	7.9×10^3	3.7×10^3	1.6×10^3	5.3×10^3	18	3.9×10^2	4.1×10^2	3.4×10^6
Copper	kg	-	-	4.5×10^4 (3)	1.0×10^2	32	1.3×10^2	7×10^1	7.8×10^3	7.9×10^3	30	3.9×10^3	3.9×10^3	9.4×10^6
Zinc	kg	-	-	3.6×10^6 (3)	9.5×10^3	64	9.6×10^3	5.3×10^3	1.6×10^4	2.1×10^4	1.1×10^2	3.9×10^3	3.9×10^3	2.9×10^7
Cadmium	kg	-	-	4.5×10^4 (3)	3.2×10^2	10	3.3×10^2	1.8×10^2	2.3×10^3	2.5×10^3	5	3.9×10^2	4.0×10^2	1.1×10^6
Mercury	kg	-	-	4.5×10^3 (3)	1.7	N/A	ca 1.7	0.9	N/A	ca. 0.9	0.1	8	8.1	3.6×10^4
Lead	kg	-	-	3.6×10^5 (3)	7.4×10^3	32	7.4×10^3	8.1×10^3	7.8×10^3	1.6×10^4	36	3.9×10^2	4.3×10^2	3.7×10^6
HYDROCARBONS														
Oil and grease (Estimates for Canadian Regions)	kg				1.9×10^5 (5)	2.5×10^3	2.0×10^5	1.0×10^5 (5)	3.1×10^6	4.2×10^6	2.7×10^4 (5)	4.0×10^5	4.3×10^5	1.9×10^7
Oil from produced water	kg	5.2×10^5 (1, Note 1)		6.8×10^5 (2)										
Oil from oily cuttings	kg	$69. \times 10^5$ (1, Note 2)												
Oil from spillage	kg	1.0×10^5 (1)												
Total	kg	75×10^5 (1, Note 3)	$20\text{-}30 \times 10^5$ (1)											

1. pers. comm. Johnston
2. Hildeman 1981. Data cover the period 1975-1978.
3. Gianessi and Arnold 1982.
4. Estimates based on production scenarios and waste characteristics given in Tables 7-4 and 7-5.
5. Includes oil and grease from drill cuttings (1.7×10^5 kg, 9.1×10^4 kg, and 2.3×10^4 kg for Scotian Shelf, Grand Banks and Beaufort Sea, respectively).
6. Thomas et al. 1983; natural flux calculated for area of the Beaufort Sea shoreward of the 200 m isobath.

NOTES:

1 Assumes all discharge from all U.K. offshore fields contains less than 40 mg/L oil (IR); this may be an underestimate because low-boiling aromatics are not recovered by the analysis.

2 Assumes oil content of 15% of the cuttings, with estimate based on total number of wells times volume discharged per well; total recovery of oil by retort analysis.

3 Based on industry reports to U.K. Department of Energy (reporting of all spills including surface sheen required).

Other factors affecting the accumulation rate are the action of bottom scouring currents, turbidity currents, high-energy sea bottom movements and ice scouring. All these processes would tend to dilute the discharged wastes. The incremental increases of metals and hydrocarbons from other sources such as sanitary and domestic wastes, and deck drainage are small compared with drilling mud discharges; therefore, these other wastes would not significantly alter the mass loadings described above.

It must be emphasized that the dispersion model results cannot be definitive because the input data are not definitive. The model results are order-of-magnitude estimates. The results are useful for comparing the different regions and different chemical components of production wastes. More accurate results and quantitative predictions can only be made when better data become available.

5.3 Oil Loadings: A Comparison of Offshore Production and Shipping Sources

The loading of oil to the Grand Banks and Scotian Shelf resulting from operational losses during offshore hydrocarbon production, as projected from the development scenarios given in Chapter 7, is compared in Table 8-20 with the existing loading resulting from shipping using the data given by Transport Canada (1978). The main sources of oil associated with petroleum production are produced water and cuttings discharge. Waste oil from bilge pumping and tank cleaning are the two main sources of operational discharges associated with shipping.

TABLE 8-20

A COMPARISON OF THE ANNUAL LOADING OF OIL TO THE WATERS OF THE GRAND BANKS AND SCOTIAN SHELF EXPECTED FROM PROPOSED OFFSHORE HYDROCARBON PRODUCTION WITH THAT RESULTING FROM EXISTING SHIPPING

	Scotian Shelf (L/year)	Grand Banks (L/year)	Shipping (L/year)
Oil associated with produced water[a]	3,000	292,000	
Oil associated with drill cuttings			
(a) For Water- base Muds[b]	100,000	535,000	
(b) For Oil- base Muds[c]	2,000,000	1,070,000	
Oil associated with ship bilge pumping[d]			920,895
Oil associated with ship tank cleaning[d]			1,625,345
TOTALS			
Water Base Muds	**103,000**	**345,500**	
Oil Base Muds	**2,003,000**	**1,362,000**	
Shipping Losses			**2,546,240**

---

[a] calculations based on data from Table 7-4

[b] water base muds assumed to contain 5% oil only 10% of the time (overall oil content is thus 0.5%)

[c] oil base muds assumed to contain 10% oil (Law and Blackman, 1981)

[d] Transport Canada, 1978

As shown in Table 8-20, the total annual discharge of oil to East Coast waters from shipping will be about five times that expected from the combined hydrocarbon production areas of the Scotian Shelf and Grand Banks if water-base drilling muds are used. If, on the other hand, oil-base drilling muds are used, the loading resulting from production would exceed that associated with shipping by about 30%.

There are no estimates for the amount of oil entering the Beaufort Sea from shipping sources. Thomas et al. (1983), however, made a very liberal estimate of the industry-related flux of oil into the Beaufort Sea resulting from chronic losses of BOP control fluid, oil and grease from well cuttings, oil and grease from produced water and non-catastrophic day-to-day accidental hydrocarbon spills. The industrial flux obtained when scaled to the oil production rate of 32,000 m^3/d used in this report, was about one-half the natural flux of hydrocarbons to the Beaufort Sea.

5.4 Sewage Loading

The rate of sewage loading to the marine environment surrounding the offshore production areas will be a direct function of the number of personnel (approx. 200-500) working in the offshore. With the exception of small changes reflecting the greater average age of the population working offshore compared with that in the general population, the discharge of sewage from production platforms would be expected to be very similar to that associated with coastal communities of 200-500 inhabitants of which there are numerous examples along the coasts of Nova Scotia and Newfoundland.

CHAPTER 8

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CHAPTER 8

PERSONAL COMMUNICATIONS

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APPENDIX A

Various approaches have been taken in bioassays with drilling fluids, including the use of whole drilling mud added to sea water and evaluation of specific fractions to simulate the types of exposure organisms in different marine habitats may encounter. The protocols for preparing each type of fraction are reviewed in Neff (1982) and include the following bioassay media:

- Liquid Phase (LP): contains the water-soluble fraction of 250,000 ppm drilling mud in water (EPA/COE 1977)

- Suspended Particulate Phase (SPP): contains the water-soluble and fine particulate fractions of 250,000 ppm drilling mud in water (EPA/COE 1977)

- Solid Phase (SP): the insoluble particulate fraction of a drilling mud (EPA/COE 1977)

- Mud Aqueous Fraction (MAF): contains the water-soluble and fine particulate fractions of 100,000 ppm drilling mud in water, and may also be filtered to produce a filtered mud aqueous fraction (FMAF) (Neff *et al*. 1980, 1981)

- Suspended Particulate Phase (SPP): resembles the MAF except that the SPP contains a higher concentration of particulates and lower concentration of volatiles (Neff *et al*. 1980, 1981)

- Suspended Solids Phase (SSP): the drilling mud and artificial sea water aerated vigorously to keep particulates in suspension (Neff *et al*. 1980, 1981)

- Layered Solid Phase (LSP): a drilling mud is layered over clean natural sediment in an aquarium and natural sea water added with minimum resuspension of mud (Neff *et al*. 1980, 1981)

A-2

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Phytoplankton (EC50 Values)			
Skeletonema costatum	Imco Lime	1,375	1
	Imco Non-Dispersed	5,700	1
	Lignosulphonate SW/FW	3,700	2
Copepods			
Acartia tonsa	Imco Lime	5,600	1
	Imco Non-Dispersed	66,500	1
	F-chrome Lignosulphonate	230	3
	Saltwater-Gel	100	4
	Light Lignosulphonate	10,000	4
	F-chrome Lignosulphonate	100	4
Eurytemora herdmani	Medium-density LS (MAF/4°)	82,000	16
	Medium-density LS (SSP/4°)	620,000	16
	Light-density LS (MAF/4°)	88,000	16
	Light-density LS (SSP/4°)	800,000	16
	Spud Mud (MAF/4°)	>100,000	16
	Spud Mud (SSP/4°)	980,000	16
Isopods			
Saduria entomon	XC-Polymer/Unical	314,000-500,000	5
	CMC-Resinex Tannathin	>530,000	5
Gnorimosphaeroma oregonensis	F-chrome LS-FW	>70,000	6
	HDLF (Cook Inlet)	>70,000	14
Amphipods			
Anisogammarus confervicolus	F-chrome LS-FW	10,000-50,000	6
	HDLF (Cook Inlet)	>70,000->200,000	14
Onisimus sp. and *Boekosimus* sp.	XC-Polymer/Unical	200,000-436,000	5
Gammarus locusta	Spud mud (whole mud)	>100,000	7
	Spud mud (MAF)	>100,000	7
	Medium-density LS	74,000-90,000	7
	High-density LS (whole)	28,000-88,000	7

A-3

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Gastropods			
Littorina littorea	Light-density LS (MAF)	>100,000	7
Thais lapillis	Light-density LS (MAF)	>100,000	7
	Light-density LS (whole)	83,000	7
	Light-density LS (SSP)	>15,000	7
Littorina littorea	Medium-density LS (whole)	>100,000	7
	High-density LS (whole)	>100,000	7
Decapords-Shrimp			
Artemia salina	F-chrome LS-FW	>100,000	6
Pandalus hypsinotus	F-chrome LS-FW	32,000-150,000	6
Crangon septemspinosa	Spud Mud (MAF)	>100,000	7
	Sea water LS (MAF)	>100,000	7
	Light-density LS (MAF)	98,000-100,000	7
	Light-density LS (whole)	71,000	7
	Light-density LS (SSP)	>15,000	7
	Medium-density LS (MAF)	>100,000	7
	Medium-density LS (SSP)	15,000	7
Pandalus borealis (Stage I larvae)	Medium-density LS (MAF)	17,000	7
	Medium-density LS (FMAF)	19,000	7
Crangon septemspinosa	High-density LS (MAF)	>100,000	7
	High-density LS (whole)	92,000	7
	High-density LS (SSP)	>15,000	7
Pandalus borealis (Stage I larvae)	High-density LS (MAF)	65,000	7
	High-density LS (FMAF)	55,000	7
Palaemonetes pugio -zoeae	Spud Mud (MAF)	>100,000	8
-adult	Spud Mud (MAF)	>100,000	8
-zoeae	SW-chrome LS (MAF)	27,500	8
-adult	SW-chrome LS (MAF)	92,400	8
-zoeae	Medium-density LS (MAF)	35,000	8
-adult	Medium-density LS (MAF)	91,000	8
-zoeae	High-density LS (MAF)	>18,000	8
-adult	High density LS (MAF)	>100,000	8

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS
(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Decapoda-Shrimp (continued)			
Pandalus borealis (Stage III)	Medium-density LS (MAF)	13,000	16
	Medium-density LS (SPP)	40,000	16
Palaemontes pugio 1-10 days	High-density LS (SPP)	11,700-13,200	8
Penaeus aztecus (juv)	SW-chrome LS (MAF)	41,500	8
	Medium-density LS (MAF)	16,000	8
Orchestia traskiana	SW-polymer (Aquitaine)	230,000	9
	Gel Chemical XC (Pelly)	80,000	9
	KCl-XC-Polymer (Pelly)	14,000	9
	Weighted Shell Polymer	34,000	9
	Weighted Gel-SX Polymer	420,000	9
	Imnak Gel-XC-Polymer	>560,000	9
Palaemonetes pugio	Unspec. Gulf of Mexico Fluids	363-739	10
Pandalus hypsinotus	Used Prudhoe Bay	76,550*	13
	New Prudhoe Bay	16,150*	13
	Used Cook Inlet	4,500*	13
	New Homer	>25,000*	13
	Used Homer	188,100*	13
	HDLF (Cook Inlet)	32,000-150,000	14
Eualus suckleyi (Stage I)	Cook Inlet F-C LS (WSF)	2,350*	13
Pandalus danae (Stage I)	Cook Inlet F-C LS (SM)	500*	13
	Cook Inlet F-C LS (WSF)	1,500*	13
Mysidopsis almyra 1-14 days	Chrome LS (MAF)	34,000-96,000	17
Palaemonetes pugio (4 day old)	Chrome LS (MAF)	34,000	17
P. pugio (post-larvae)	Chrome LS (MAF)	67,000	17
P. pugio (adults)	Chrome LS (MAF)	90,000	17

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Decapods-Crabs			
Carcinus maenas	Light-density LS (MAF)	>100,000	7
	Light-density LS (WMF)	89,000	7
	Light-density LS (SSP)	>15,000	7
	Medium-density LS (MAF)	>100,000	7
	Medium-density LS (whole)	68,000	7
	Medium-density LS (SSP)	>15,000	7
	High-density LS (MAF)	>100,000	7
Clibanarius vittatus	SW-chrome LS (MAF)	28,700	8
	Medium-density LS (MAF)	34,500	8
	High-density LS (MAF)	65,600	8
Hemigrapsus nudus	Seawater Polymer	530,000	9
	Shell KCl Polymer	53,000	9
	KCl-XC-Polymer	78,000	9
	Gel Chemical XC	>560,000	9
	Weighted Shell Polymer	62,000	9
	Weighted Gel-XC-Polymer	560,000	9
	Imnak Gel-XC-Polymer	>560,000	9
Paralithodes camschatica (Stage I larvae)	New Prudhoe Bay	11,650*	13
	Used Cook Inlet	16,700*	13
	Used Homer Spud	47,250*	13
	New Homer	35,850*	13
	Used Homer	150,400*	13
	Cook Inlet F-C LS (SM)	4,800*	13
	Cook Inlet F-C LS (WSF)	16,700*	13
Cancer magister (Stage I)	Cook Inlet F-C LS (SM)	2,000*	13
	Cook Inlet F-C LS (WSF)	7,050*	13
Chionoccetes bairdii (Stage I)	Cook Inlet F-C LS (SM)	9,400*	13
	Cook Inlet F-C LS (WSF)	8,250*	13
Cancer borealis	Medium-density LS (MAF)	>100,000	16
	Medium-density LS (whole)	960,000	16

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Decapods-Lobster			
Homarus americanus			
-larvae	Light-density LS (MAF)	5,000	7
-adult	Light-density LS (MAF)	>100,000	7
-adult	Light-density LS (WMF)	19,000-25,000	7
-larvae	Medium-density LS (MAF)	>100,000	7
-larvae	Medium-density LS (WMF)	29,500	7
Bivalve Molluscs			
Modiolus modiolus	F=chrome LS-FW	>30,000	6
Mytilus edulis	Spud Mud (MAF)	>100,000	7
	Sea water LS (MAF)	>100,000	7
Macoma balthica	Light-density LS (MAF)	>100,000	7
	Light-density LS (whole)	>100,000	7
	Light-density LS (SSP)	>15,000	7
Placopecten magellanicus	Light-density LS (whole)	49,000	7
Mytilus edulis	Medium-density LS (MAF)	>100,000	7
	Medium-density LS (SSP)	>15,000	7
Placopecten magellanicus	Medium-density LS (whole)	< 3,200	7
Mytilus edulis	High-density LS (MAF)	>100,000	7
	High-density LS (SSP)	>15,000	7
Macoma balthica	High-density LS (MAF)	>100,000	7
	High-density LS (whole)	>100,000	7
Crassostrea gigas	Medium-density LS (SPP)	50,000-53,000	8
Donax variabilis	Spud Mud (SPP)	>100,000	8
	SW-chrome LS (SPP)	53,700	8
	Medium-density LS (SPP)	29,000	8
	High-density LS (SPP)	56,000	8

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Decapods-Lobster			
Mya arenaria	Seawater Polymer	320,000	9
	Shell KCl Polymer	42,000	9
	Gel Chemical XC	>560,000	9
	KCl-XC-Polymer	56,000	9
	Weighted Shell Polymer	10,000	9
	Weighted Gel-XC Polymer	>560,000	9
	Weighted KCl-XC Polymer	>560,000	9
	Imnak Gel-XC-Polymer	>560,000	9
Placopecten magellanicus	Medium-density LS (MAF/4.5°)	>100,000	16
	Medium-density LS (WM/4.5°)	7,000	16
Donax variabilis (juv)	Chrome LS (MAF)	>100,000	17
(adult)	Chrome LS (MAF)	86,000	17
Mercenaria campechiensis	Chrome LS (MAF)	>100,000	17
Rangia cuneata	Chrome LS (MAF)	>100,000	17
Echinoderms			
Strongylocentrotus droebachiensis	Light-density LS (MAF)	>100,000	7
	Light-density LS (whole)	55,000	7
	Medium-density LS (MAF)	>100,000	7
	Medium-density LS (swhole)	>100,000	7
Mysids			
Neomysis integer	F-chrome LS-FW	10,000-200,000	6
	HDLF (Cook Inlet)	10,000-125,000	14
Mysis sp.	CMC-Gel-Resinex	< 60,000	5
	XC-Polymer	50,000-170,000	5

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Mysids			
Mysidopsis almyra			
-1-7 days	Spud Mud (MAF)	>100,000	8
-1 day	SW-chrome LS (MAF)	27,000	8
-1-7 days	Medium-density LS (MAF)	12,800-13,000	8
-1-7 days	High-density LS (MAF)	>16,000-32,500	8
-1 day	Medium-density LS (MAF)	26,800-42,000	11
-3-10 days	Medium-density LS (MAF)	66,300-113,000	11
Mysidopsis bahia	SW-Lignosulfonate (LP)	56,700	15
	SW-Lignosulfonate (SPP)	10,640	15
	Lime Mud (LP)	78,600	15
	Lime Mud (SPP)	13,200	15
	Seawater Spud Mud (LP)	>200,000	15
	Seawater Spud Mud (SPP)	>200,000	15
	SW/FW Gel Mud (LP)	>200,000	15
	SW/FW Gel Mud (SPP)	44,800	15
	Light LS-FW/SW (LP or SPP)	>200,000	15
	Lignosulfonate FW (LP)	>200,000	15
	Lignosulfonate FW (SPP)	101,200	15
Polychaetes			
Nereis virens	Spud Mud (MAF)	>100,000	7
	Seawater LS (MAF)	>100,000	7
	Light-density LS (MAF or whole)	>100,000	7
	Medium-density LS (MAF or whole)	>100,000	7
	High-density LS (MAF or whole)	>100,000	7
Ophryostrocha labronica	Spud Mud (MAF)	>100,000	8
	SW-chrome LS (MAF)	>100,000	8
	Medium-density LS (MAF)	60,000	8
	High-density LS (MAF)	[illegible],000	8
Nereis vexillosa	Seawater Polymer	220,000	9
	Shell KCl Polymer	37,000	9
	Gel Chemical XC	>560,000	9
	KCl-XC-Polymer	41,000	9

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Polychaetes			
Nereis vexillosa (cont'd)	Weighted Shell Polymer	23,000	9
	Weighted Gel-XC-Polymer	320,000	9
	Imnak-Gel-XC-Polymer	200,000	9
Neanthes arenaceodentata (juveniles)	Chrome LS (MAF)	96,000	17
Neanthes arenaceodentata (adults)	Chrome LS (MAF)	51,000	17
Ophryostrocha labronica	Chrome LS (MAF)	>100,000	17
Dinophilus sp.	Chrome LS (MAF)	32,000	17
	Chrome LS (FMAF)	45,000	17
Finfish			
Menidia menidia	Saltwater Gel	100,000	12
	Light LS SW/FW	48,500	12
	F-chrome LS	100,000	12
Oncorhynchus gorbuscha	F-chrome LS-FW	3,000-29,000	6
Myoxocephalus quadricornis	XC-Polymer	50,000-215,000	5
	Lignosulfonate	350,000	5
Coregonus nasus	XC-Polymer	64,000-370,000	5
	Lignosulfonate	100,000	5
Elogonus navaga	CMC-Gel	170,000-300,000	5
Boreogadus saida	XC-Polymer	>250,000	5
	Lignosulfonate	200,000-250,000	5
Coregonus autumnalis	Lignosulfonate	400,000	5

ACUTE LETHAL CONCENTRATIONS OF WHOLE DRILLING MUDS WITH REPRESENTATIVE MARINE ORGANISMS

(96-h LC50 unless otherwise indicated; adapted from Petrazzuolo 1981)

TAXON/ORGANISM	MUD SYSTEM	CONC. (ppm)	REFERENCE
Fundulus heteroclitus	Spud Mud (MAF)	>100,000	7
	Sea water LS (MAF)	>100,000	7
	Medium-density LS (MAF)	>100,000	7
	Medium-density LS (SSP)	>15,000	7
	High-density LS (MAF)	>100,000	7
	High-density LS (SSP)	>15,000	7
Lettococcus armatus	HDLF (Cook Inlet)	100,000-200,000	14
Salmo gairdneri	Shell KCl Polymer	24,000	9
Oncorhynchus kisutch	Shell KCl Polymer	29,000	9
O. keta	Shell KCl Polymer	24,000	9
O. gorbuscha	Shell KCl Polymer	41,000	9
	HDLF (Cook Inlet)	3,000-29,000	14
O. kisutch	Aquitaine SW Polymer	130,000	9
	KCl-XC-Polymer	23,000	9
	Weighted Shell Polymer	15,000	9
	Gel-Chemical-XC	39,000	9
	Weighted Gel-XC-Polymer	190,000	9
	Imnak-Gel-XC-Polymer	30,000	9

Common Names of Finfish Species

Menidia menidia	Atlantic silversides
Myoxocephalus quadricornis	Fourhorn sculpin
Coregonus nasus	Broad whitefish
Elegonus navaga	Saffron cod
Boreogadus saida	Arctic cod
Coregonus autumnalis	Arctic cisco
Fundulis heteroclitus	Killifish
Salmo gairdneri	Rainbow trout
Oncorhynchus kitsutch	Coho salmon
O. keta	Chum salmon
O. gorbuscha	Pink salmon
Leptococcus armatus	Pacific staghorn sculpin

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INDEX

(prepared by Doris Stastny)

f = information occurs in a figure
t = information occurs in a table

- Acronyms, initials
  - BOP fluid = blowout preventer fluid
  - CGS = Central Gulf-of-Mexico-Platform Study
  - CODC Act = Canada Ocean Dumping Control Act
  - COGLA = Canadian Oil and Gas Lands Administration
  - C.O.S.T. = Continental Offshore Stratigraphic Test
  - CPI = corrugated plate interceptor
  - EPA = Environmental Protection Agency (U.S.)
  - MAFLA OCS Investigation = Mississippi, Alabama, Florida Outer Continental Shelf Investigation
  - MARPOL = International Convention for the Prevention of Pollution from Ships, 1973
  - NPDES = National Pollution Discharge Elimination System (U.S.)
  - OCS = Outer Continental Shelf
  - OEI = Offshore Ecology Investigation
  - PAH = polycyclic aromatic hydrocarbons
  - RBC = rotating biological contactor
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